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COVID-19 Impact on Operation and Energy Consumption of Heating, Ventilation and Air-Conditioning (HVAC) Systems

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ABSTRACT

Heating, ventilation and air-conditioning (HVAC) system is favourable for regulating indoor temperature, relative humidity, airflow pattern and air quality. However, HVAC systems may turn out to be the culprit of microbial contamination in enclosed spaces and deteriorate the environment due to inappropriate design and operation. In the context of COVID-19, significant transformations and new requirements are occurring in HVAC systems. Recently, several updated operational guidelines for HVAC systems have been issued by various institutions to control the airborne transmission and mitigate infection risks in enclosed environments. Challenges and innovations emerge in response to operational variations of HVAC systems. To efficiently prevent the spread of the pandemic and reduce infection risks, it is essential to have an overall understanding of impacts caused by COVID-19 on HVAC systems. Therefore, the objectives of this article are to: (a) provide a comprehensive review of the airborne transmission characteristics of SARS-CoV-2 in enclosed spaces and a theoretical basis for HVAC operation guideline revision; (b) investigate HVAC-related guidelines to clarify the operational variations of HVAC systems during the pandemic; (c) analyse how operational variations of HVAC systems affect energy consumption; and (d) identify the innovations and research trends concerning future HVAC systems. Furthermore, this paper compares the energy consumption of HVAC system operation during the normal times versus pandemic period, based on a case study in China, providing a reference for other countries around the world. Results of this paper offer comprehensive insights into how to keep indoor environments safe while maintaining energy-efficient operation of HVAC systems.

1. Background

The COVID-19 infectious disease caused by the SARS-CoV-2 virus continues to spread around the world unchecked since the end of 2019. On March 1, 2020, the World Health Organization (WHO) declared COVID-19 a global pandemic. The COVID-19 pandemic forced many countries to quickly adopt measures such as social distancing and even lock-downs. However, all of these actions have a significant negative impact on national economies disrupted by the collapse of commerce, tourism, manufacturing and international trade and services. This has led to increased unemployment, closing down of businesses, reduced

Abbreviations: AHU, air handing unit; ASC, Architectural Society of China; ASHRAE, American Society of Heating Refrigerating and Air-Conditioning Engineers; CAR, Chinese Association of Refrigeration; CCIAQ, Canadian Committee on Indoor Air Quality; COP, coefficient of performance; DCV, demand-controlled ventilation; ECDC, European Centre for Disease Prevention and Control; EEAF, electrostatic enhanced air filter; EEPF, electrostatic enhanced pleated air filters; HEPA, high efficiency particulate air; HPHE, heat pipe heat exchanger; EPA, Environmental Protection Agency; HVAC, heating, ventilation and air-conditioning; ISHRAE, Indian Society of Heating Refrigerating and Air Conditioning Engineers; MERV, minimum efficiency reporting value; MOHURD, Ministry of Housing and Urban-Rural Development of the People's Republic of China; NHC, National Health Commission of China; PHO, Public Health Ontario; REHVA, Federation of European Heating Ventilation and Air Conditioning Associations; SAC, Standardization Administration of the People's Republic of China; SBS, sick building syndrome; SHASE, Society of Heating Air-Conditioning and Sanitary Engineers in Japan; UV, ultraviolet; UVGI, ultraviolet germicidal irradiation; WHO, World Health Organization.

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Nomenclature

E	energy consumption of HVAC systems (kWh)
h	enthalpy (kJ/kg)
m	mass flow of air (kg/s)
Q	hourly HVAC load provided by the equipment (kWh)
r	Pearson correlation coefficient
x	influencing factor
y	increasing ratio of HVAC system energy consumption in winter and summer

Greek symbols

α	ratio of HVAC load between the normal times and pandemic period

Subscripts

i	indoor air
n	normal times
o	outdoor air
p	pandemic period
r	return air
s	supply air

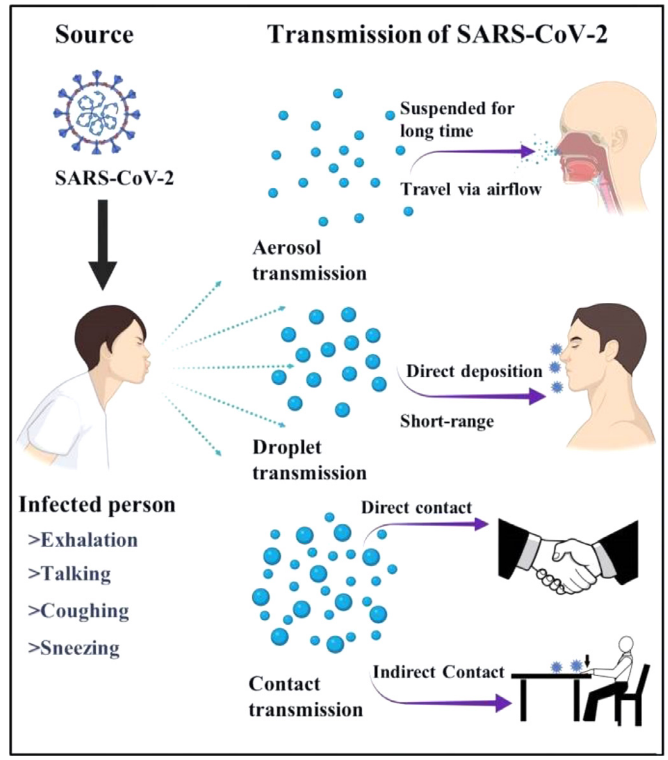


Fig. 1. Main transmission modes of SARS-CoV-2. (Reproduced from Ref. 6.)

gross domestic product, and slowed down or even reversed economic development as reported by Kumar and Morawska [1].

During the COVID-19 pandemic, the time spent indoors is extended due to the limitation of outdoor activities. While investigating aerosol transmission of SARS-CoV-2, Pease and others [2] noted that the potential transmission of the disease in enclosed spaces has drawn attention from both government institutions and researchers across the globe. Hwang and others [3] investigated SARS-CoV-2 transmission in an apartment in Seoul, Korea, and found that SARS-CoV-2 could be transmitted by aerosols, especially in indoor environments without sufficient ventilation. Surveillance conducted in a restaurant in China by Li and others [4] showed an infection between two customers who had no direct contact; this provided evidence for the airborne transmission of SARS-CoV-2 in enclosed spaces. The WHO has reported that the transmission of SARS-CoV-2 includes contact, droplet, aerosol and contaminant transmission [5]. The main transmission modes of SARS-CoV-2 are shown in Fig. 1. In addition to contact and droplet transmission, Priyanka and others [6] reported that airborne transmission has shown to be the major transmission mode of SARS-CoV-2, especially in enclosed spaces.

Aerosols are the main medium of airborne transmission for SARS-CoV-2, characterized by a small particle size and a long survival time in the air, so the transmission ability of the virus is greatly impacted by airflow. Poor ventilation can exacerbate aerosol transmission, and there is a wealth of evidence to support this claim. Guo and others [7] found a large number of positive samples by testing the air in different locations of Huoshenshan Hospital. Studies by Chen and others [8] and Liu and others [9] confirmed the presence of positive samples in the air. The spread of SARS-CoV-2 following exposure at a choir practice in Washington on March 17, 2020, from which 32 confirmed cases as well as 20 close contacts were diagnosed, was investigated by Hamner and others [10]. A similar situation in France on March 12, 2020, where 19 participants were diagnosed with COVID-19 after a choir practice in a non-ventilated space, was reported by Charlotte [11], further confirming that choir practices presented high possibility of airborne transmission. The above incidents clearly demonstrate that transmission cases can be associated with poor ventilation. Furthermore, Lu and others [12] found that a COVID-19 outbreak in a restaurant in Guangzhou, China, was caused by a weak ventilation system. A pandemic of the Middle East Respiratory Syndrome in a South Korean emergency room in 2015, caused by a single patient, was cited by Cho and others [13] as a possible result of poor ventilation and high population density. In addition to buildings, Shen and others [14] noted the general perception that public transportation is an important factor contributing to the spread of the disease. Gupta and others [15] proposed that poor ventilation could increase the risk of airborne transmission due to the microorganism propagation via the vehicle's exhaust system. The pandemic outbreak on the Diamond Princess cruise ship resulted in 712 cases being diagnosed with COVID-19 as reported by Statista [16]. Murphy and others [17] reported that on a flight to Dublin, 13 out of 49 people on board were infected with COVID-19. As reported by Shen and others [18], 23 out of 67 people were infected during a bus ride, which led to the conclusion that even short trips were risky. Therefore, the US Centres for Disease Control (as shown in Fig. 2) concluded that ventilation, a traditional infection control method, can improve indoor air quality and is effective in reducing the airborne transmission of SARS-CoV-2 [19]. Ventilation plays a key role in eliminating exhaled air carrying viruses by reducing the dose inhaled by occupants through diluting the concentration of viruses. Ram and others [20] found that ventilation also changes the location of SARS-CoV-2 and reduces the accumulation of viruses if the airflow pattern is appropriate. It is worth noting that filtration and sterilization are required to purify the exhaust air and to prevent other areas from being contaminated.

During the normal times (i.e., non-pandemic times), heating, ventilation and air-conditioning (HVAC) systems in buildings are designed to remove indoor heating/cooling load and contamination (mainly CO_2 and respirable suspended particulates). However, during the COVID-19 pandemic, HVAC systems should also be able to eliminate indoor SARS-CoV-2 as presented in Fig. 3.

Considering the role of HVAC systems in controlling the spread of SARS-CoV-2 in the air, many building control authorities and associations in various countries have issued updated guidelines on the operation and management of HVAC systems during the pandemic period. Guo and others [21] reviewed and compared the guidelines issued by different countries. Up to now, several countries around the world including China [22], Japan [23], India [24], USA [25], EU [26], and Canada [27] have successively published guidelines to counter COVID-

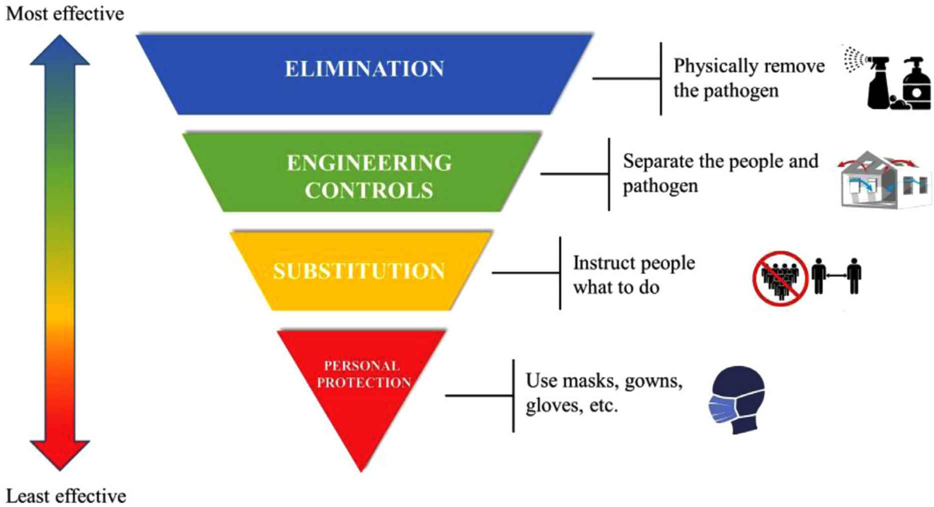


Fig. 2. Traditional infection control methods adapted from the US Centres for Disease Control. (Modified from Ref. 19.)

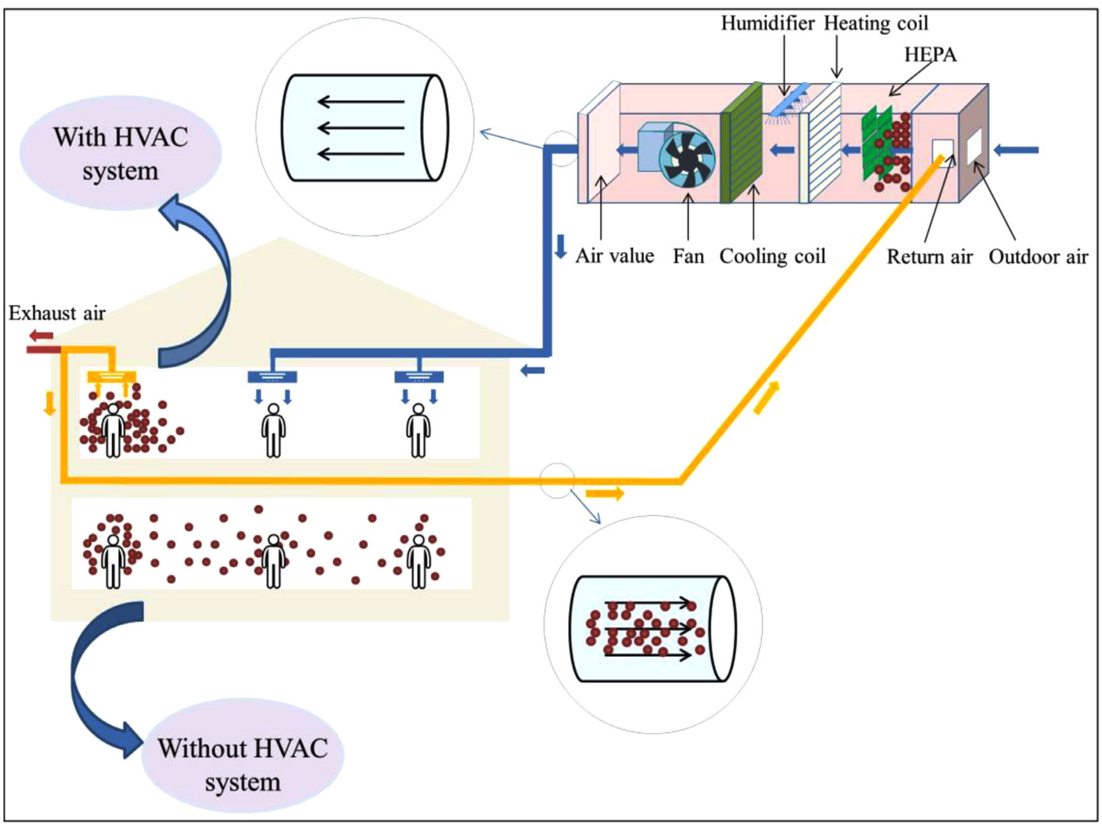


Fig. 3. Effect of a HVAC system on the prevention and control of COVID-19.

19. These various guidelines propose countermeasures such as increasing outdoor air volume, applying auxiliary equipment and adjusting operation strategies. Although these measures have the potential to reduce infection risks, they can also result in extra energy consumption and cost. Numerous studies investigate the relationship between countermeasures and energy consumption. Santos and Leal [28] assessed the question of energy versus ventilation and found that high ventilation rates increased energy consumption. Furthermore, the US Environment Protect Agency (EPA) reported on the energy cost and indoor air quality performance of ventilation rates [29]. Dutton and Fisk [30] investigated the energy and indoor air quality implications of alternative minimum ventilation rates in California. A case study was conducted by Ozyogurtcu and others [31] into the economics of HVAC systems with various outdoor air volume in Turkey. Long and Lin [32] reported relative variation rates of HVAC energy consumption with a same ventilation rate in different cities. Vakiloroaya and others [33] reviewed the different strategies for HVAC energy savings. Relevant works on HVAC systems have been reported by Zaatari and others [34] on particulate filter performance and energy consumption, and by Vranay and others [35] on adaptation of ultraviolet germicidal irradiation (UVGI) systems to reduce the spread of SARS-CoV-2. They have studied the relationship between countermeasures and energy consumption in some respects, while an overall insight into COVID-19 impacts on HVAC operation and energy consumption is still need further investigation. The trade-off between greater energy consumption and indoor air quality in the context of the pandemic is well worth the consideration and analysis.

Compared with previous literature, this paper analyses the ability of HVAC systems to control the transmission of SARS-CoV-2 and corresponding energy impacts of HVAC systems from a systematic and overall perspective. Furthermore, a case study of China is conducted to give a quantitative analysis of HVAC energy consumption variations in the context of COVID-19. The above contents were rarely discussed from a comprehensive perspective in previous literature but they are meaningful and valuable for guiding COVID-19 countermeasures. To effectively prevent and control the pandemic, it is essential to have an overall understanding of the impacts caused by COVID-19 on HVAC systems. Therefore, this article presents: (a) a comprehensive review of the airborne transmission characteristics of SARS-CoV-2 in enclosed spaces; (b) various guidelines on the operation of HVAC systems during the pandemic; (c) an analysis on how operational variations of HVAC systems impact energy consumption; and (d) innovations and research trends impacting on future HVAC systems. This paper offers insights and actions for HVAC engineers and epidemiologists on how to make HVAC systems energy efficient whilst simultaneously maintaining the indoor environment safe and comfortable for human occupants. Furthermore, this paper establishes a foundation for future work and presents insights on novel research trends. The structure of this paper is presented as shown in Fig. 4.

2. Airborne transmission of COVID-19 in an enclosed space

The COVID-19 pandemic has greatly impacted the global economy and energy application, whilst making people more aware of the potential transmission modes of SARS-CoV-2. Airborne transmission is considered as one of the major transmission modes in the enclosed spaces and ventilation is proposed as an effective method to dilute and remove indoor aerosols. A profound discussion of airborne transmission mechanisms of SARS-CoV-2 can provide a theoretical basis for HVAC operation to prevent and control the pandemic. Furthermore, analysis of energy impacts of COVID-19 on HVAC systems can be achieved based on the variations of HVAC system operation. Therefore, this chapter introduces the properties and propagation mechanisms of aerosols while the impact of introducing outdoor air and the effectiveness of traditional ventilation, as measures of reducing airborne transmission, are discussed in detail. Furthermore, this chapter introduces the characteristics of virus transmission in certain special enclosed spaces such as aircraft, trains and buses. In such spaces, the occupancy is dense and the virus can spread rapidly.

2.1. Principles of airborne transmission

2.1.1. Role of aerosols in air propagation

Airborne transmission of SARS-CoV-2 typically involves a confirmed case as a carrier of SARS-CoV-2, and the expulsion of viruses into the air through aerosols produced in his respiratory tract. Subsequently, the aerosols with SARS-CoV-2 move and decay in the air, causing the spread of infection when the aerosols encounter susceptible people as presented in Ref. 2. Furthermore, Fig. 5 provided by Ai and Melikov [36] on airborne spread of expiratory droplet nuclei shows the whole process of indoor air transmission. The general governing flows of droplet nuclei dispersion are also presented in Fig. 5.

Therefore, airborne transmission is also called aerosol transmission. Comprehending the properties of aerosols is of great significance for understanding the airborne transmission of COVID-19.

2.1.2. Aerosol generation

Aerosols can be produced by atomization of virus-containing body secretions and excreta such as the atomization of respiratory secretions by human daily behaviour and medical behaviour or, as reported by Johnson and others [37], by the atomization of faeces by flushing toilets. Dutra [38] noted that in a narrow sense, aerosol refers to the "droplet nucleus" formed by the evaporation of droplets produced by the human respiratory tract in the air. This definition is also adopted in this present work. Here, the concept of "cut-off size" for droplet and aerosol are 5 μm, as shown in Fig. 6.

There is a strong correlation between droplets and the generation of aerosols. Processes like breathing, talking, coughing and sneezing can produce droplets and aerosols, while the quantity, diameter and jet velocity of droplets as well as aerosols are different. Table 1 shows detailed information regarding droplets and aerosols generated by human expiratory activities. Hasan and others [39] studied the characteristics of airborne bioaerosol droplets generated during simulated coughing. The transmission of SARS-CoV-2 by droplets and aerosols was reported by Jayaweera and others [40]. Furthermore, Chao and others [41] reported the characterization of expiration air jets and droplet size at the mouth opening. All in all, it can be concluded that particle size and initial velocity have a great impact on the diffusion range of droplets and aerosols in enclosed environments.

2.1.3. Aerosol transmission path

The process of aerosol transmission in the air includes **evaporation, interaction with other droplets and deposition on the surface of objects.** All of these affect the life span of aerosols in airborne transmission as reported by Morawska [42].

As shown in Fig. 7 (a), evaporation can affect the life span of an aerosol by changing its size. Large aerosols are rapidly settled by gravity, while small aerosols can be suspended in the air for several hours as reported by Blocken and others [43]. The evaporation of droplets is mainly related to the environmental relative humidity. Droplets released by the respiratory tract speed up evaporation in environments characterized by low relative humidity (less than 40%) and high temperature. In their study on the movement of droplets indoors, Xie and others [44] concluded that evaporation can lead to a rapid reduction in particle size, which caused more droplets to disperse in the air as aerosols, increasing the spread and longevity of viruses. In the process of aerosol propagation, some small aerosols stick together to form large aerosols; the formation of large aerosols (coalescence phenomenon) in an indoor environment could lead to faster settlement.

The life span of aerosols attached to an object is different from that of aerosols floating in the air. Generally speaking, aerosol survival time is up to three hours. Li [45] found that the life span of a viral aerosol was less than 48 hours in a dry environment, and its activity was greatly reduced after two hours. However, the life time of an aerosol is substantially increased or decreased when it is attached to an object, and this mainly depends on the nature of the object. Doremalen and others [46] found that aerosols can last for 4, 24, 48, 72 and 84 hours on copper, cardboard, stainless steel, plastic and glass, respectively.

As shown in Fig. 7 (b), ventilation systems play a great role in aerosol transmission. The appropriate introduction of outdoor air can change the propagation path and concentration of aerosols, and decrease the amount of human adhesion. Therefore, a well-maintained ventilation system can greatly mitigate the infection risks via airborne transmission, such as COVID-19.

2.2. Impacts of ventilation on airborne transmission

The possibility of virus aggregation becomes more likely in indoor environments with high crowd density and stable air recirculation due to the airborne transmission of SARS-CoV-2. Such conditions increase infection risks in indoor environments. Ventilation can introduce outdoor air to avoid the accumulation of indoor viruses, and this is recognized as an efficient method for controlling the airborne transmission of viruses. Two groups of researchers, Luongo and others [47] and Li and others [48] investigated the role played by ventilation in the transmission of airborne infectious agents in the built environment. This section introduces the mechanisms and measures of ventilation to control the airborne transmission of viruses, thus, forming the basis for the prevention and control of COVID-19, as well as for the appropriate design

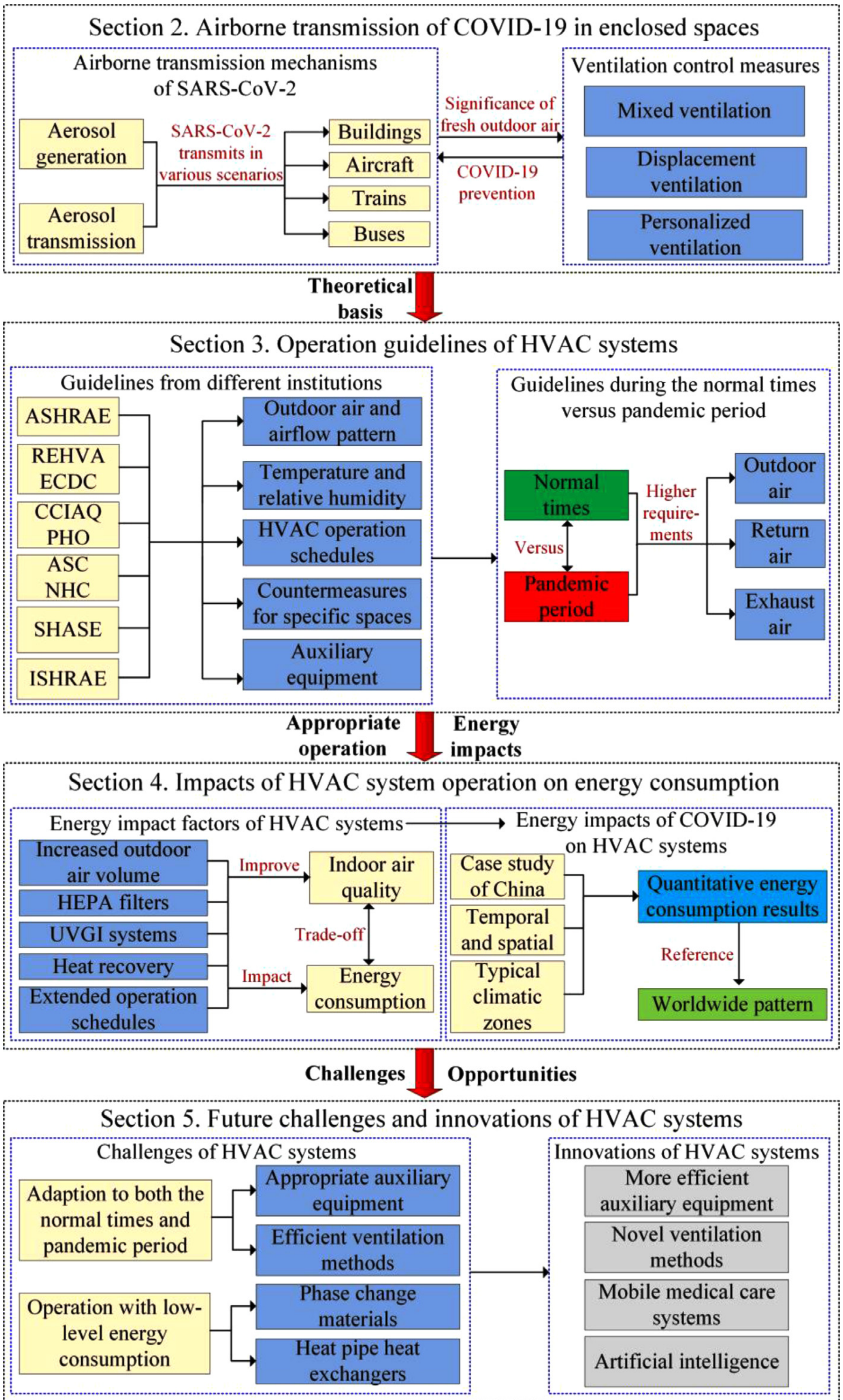


Fig. 4. A schematic overview of the structure of this paper.

Table. 1
Detailed information regarding droplets and aerosols generated by human expiratory activities.

Activity	Number of droplets and aerosols	Diameter of droplets and aerosols	Jet velocity
Normal breathing	10,000 [39]	less than 1 micron [40]	N/A
Talking	N/A	up to 60 microns [40]	3.1 m/s [41]
Single cough	thousands to 100,000 [39]	0.5 to 30 microns [40]	11.7 m/s [41]
Single sneeze	40,000 to 2 million 10000 [39]	0.5 to 16 microns [40]	100.0 m/s [41]

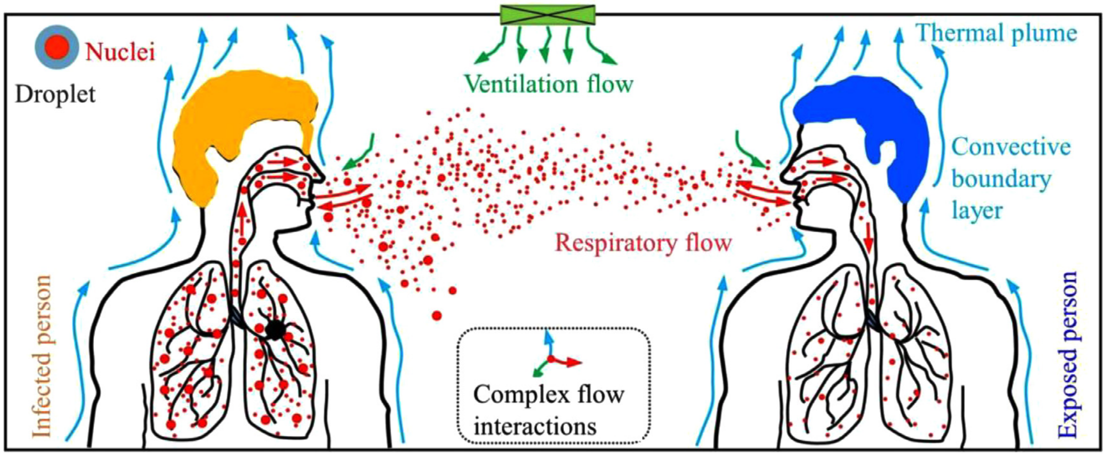


Fig. 5. A schematic overview of the airborne transmission in an enclosed environment. (Reproduced from Ref. 36.)

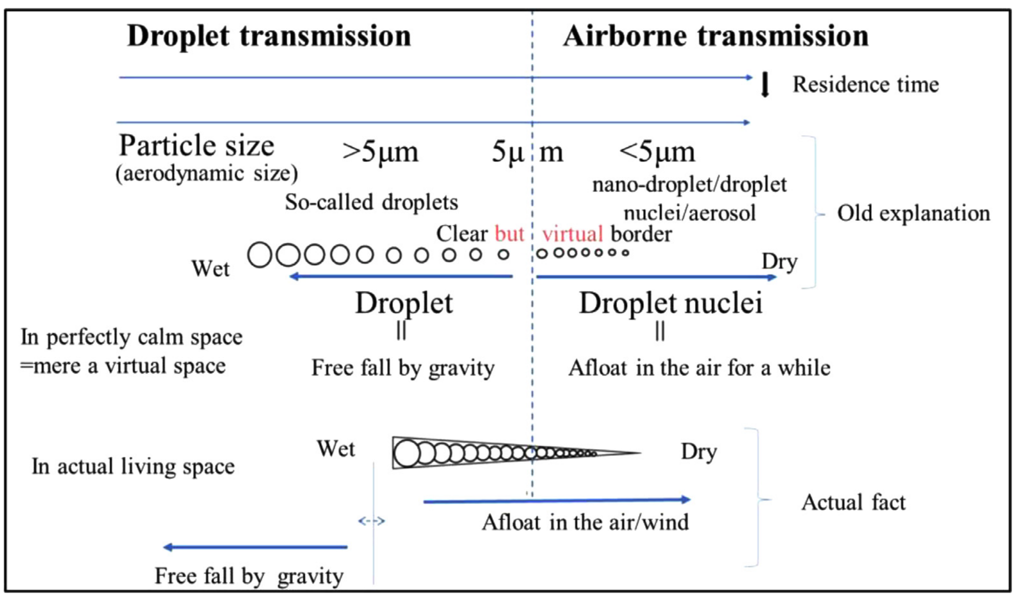


Fig. 6. Mechanism of droplet and airborne transmission. (Reproduced from Ref. 20.)

and operation of future HVAC systems. Furthermore, energy impacts of COVID-19 on HVAC systems will be discussed in the Section 4 based on the variations of HVAC systems.

2.2.1. Mechanisms of ventilation control for indoor environments

A well-designed ventilation system can cut off the transmission of contaminated airflow to other occupied areas, and can dilute viral concentration to mitigate infection risks, while a poorly designed air supply system can aggravate viral spread. Therefore, it is necessary to study the mechanism of ventilation to control the airborne transmission of viruses. As illustrated in Table 2, the principle of ventilation to control the airborne transmission of viruses mainly includes two aspects, namely, diluting viral concentration and blocking virus transmission.

Besides recommendations by WHO in Ref. 5, several studies have been carried out to address ventilation methods, system designs and control measures. Diluting viral concentration can lead to a reduction of infection risks. Methods to control and minimize aerosol transmission and ways to increase outdoor air volume in the indoor environment are described by Tang and others [49], and Lidia and others [50]. A study by Menzies and others [51] on hospital ventilation and risk of infection and another study by Hoge and others [52] on an epidemic in a crowded inadequately ventilated jail showed that lower ventilation rates could lead to higher infection risks. As a result, more attention has been paid to increase outdoor air volume, which can dilute viruses to a certain concentration and mitigate infection risks as reported by Ref. 5 and Jiang and others [53]. The airflow pattern in indoor environments determines the transmission paths of aerosols, so the airflow pattern in the room has a great impact on the airborne transmission of viruses. An appropriate airflow pattern can block the airborne transmission of viruses, and can avoid the build-up of viral contamination as reported by Bolashikov and Meikov [54] in their study on methods for air cleaning, by Melikov [55] in addressing ventilation paradigms of reducing airborne transmission, and by Olmedo and others [56] in their study on the distribution of exhaled contaminants. At the same time, an inappropriate airflow pattern will increase the probability of infectious diseases in studies carried out by Yu and others [57], Olmedo and others [58], and Qian and others [59].

2.2.2. Ventilation control measures

It is clear that the introduction of outdoor air can reduce the concentration of viruses in the air and mitigate the risk of airborne transmission as presented in Ref. 21. Air recirculation is a common energy-saving measure in HVAC systems, but it should be noted that air recirculation can transport viruses from one space to another within the same system

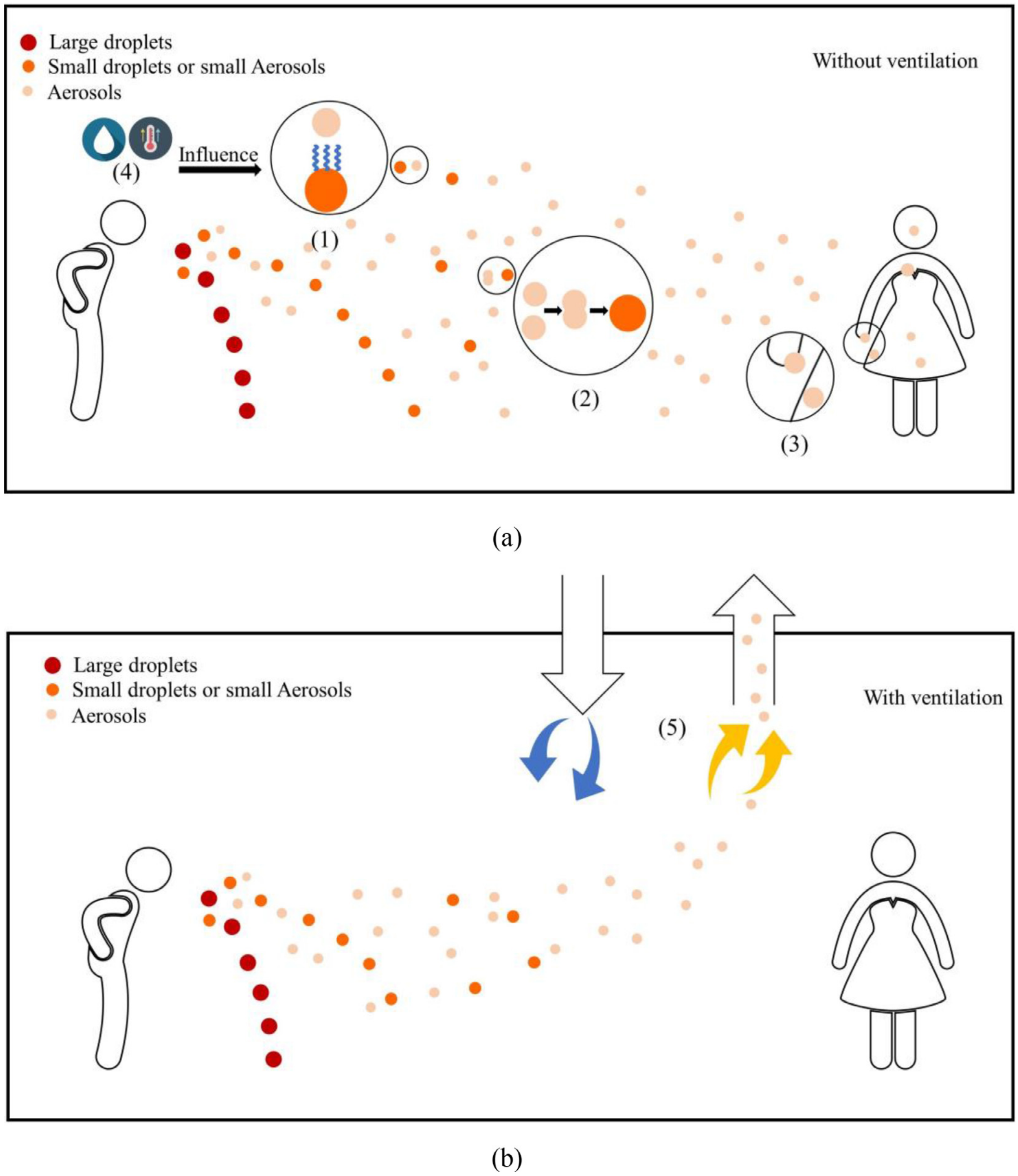


Fig. 7. Aerosol propagation path and the role of ventilation systems: (1) evaporation; (2) interaction with other droplets; (3) deposition on the surface of objects; (4) impact of temperature and relative humidity; (5) ventilation.

resulting in increased infection risks. In order to ensure low viral concentration and to avoid cross infection, HVAC systems need to operate in maximal outdoor air mode during the COVID-19 pandemic period as reported by Ref. 5. ASHRAE proposed that the outdoor air volume of ventilation systems should be increased during the pandemic, so that the outdoor air rate can be as high as 100% if possible. Other guidelines and documents also emphasize the importance of increasing the outdoor air ratio and the opening of windows as much as possible to increase the introduction of outdoor air.

Mixed ventilation refers to a form in which supply air is completely mixed with indoor air to create a uniform environment. Therefore, viruses are almost completely mixed in the occupied area and removed through the dilution process as reported by Hocking [63]. Under the condition of mixed ventilation, viruses exhaled by occupants are rapidly diluted and diffused into the air. This, as reported by Liu and others [64], greatly reduces the risk of cross infection, making mixed ventilation suitable for hospital buildings. Study in Ref. 59 simulated the nucleus of exhaled droplets from patients, and measured the spatial distribution of droplets concentration. The experimental results showed that the jet had short penetration distance and was rapidly diluted by ventilation air under both mixing and downward ventilation conditions, providing that mixed ventilation systems are practical for hospital wards with multiple beds.

Displacement ventilation can meet the requirements of indoor environments by replacing indoor air with outdoor air. Displacement ventilation causes a stratification phenomenon when it is used to remove small viral aerosols from a room. Consequently, a clean zone forms in the lower position, while a contaminated zone forms in the upper position as shown in a CFD study by He and others [65] on exhaled substance exposure of two manikins. Displacement ventilation can provide satisfactory indoor air quality in occupied areas and protect the exposed occupants from contamination. Zhan and others [66] studied the impact of airflow pattern on virus distribution and found that the number of suspended viruses associated with displacement ventilation were far less than that

Table. 2
Overview of studies dedicated to mechanisms of ventilation control in indoor environments.

Author (s)	Research scenario	Method	Conclusion	Remarks
Tang and others [49]	N/A	Survey	Adequate natural ventilation and increased hourly air exchange rate can reduce the airborne transmission of COVID-19.	Increase ventilation to dilute viral concentration.
Morawska and others [50]	N/A	Review	Increasing the present hourly air exchange rate can enhance ventilation effectiveness.	
Menzies and others [51]	Wards	Survey	The risk of airborne bacteria increases significantly in wards with hourly air exchange rate less than two.	
Hoge and others [52]	Prisons	Experiment	The cell with the lowest outdoor air volume has the highest prevalence rate.	
Jiang and others [53]	Hospitals	Simulation	10000 units of clean air is needed when a SARS patient exhaled 1 unit of contaminated air.	
WHO [5]	COVID-19 infective wards	N/A	At least 160 L/(s•person) have to be provided if natural ventilation is used.	
Bolashikov and others [54]	N/A	Review	Advanced methods for air distribution in enclosed environments are needed for protecting people from cross infection.	Use appropriate airflow pattern to block the airborne transmission of viruses.
Melikov and others [55]	N/A	Survey	Significant mitigation of infection risks with less air supply flow rate (less energy consumed) is achieved with the personalized ventilation.	
Olmedo and others [56]	Full-scale rooms	Experiment	Experiments show almost no exposure of contamination for two manikins in the context of mixed ventilation.	
Yu and others [57]	Residential areas	Simulation	The infection in the residential areas is mainly caused by inappropriate airflow pattern.	
Olmedo and others [58]	Full-scale rooms	Experiment	Inappropriate airflow pattern such as downward ventilation can increase infection risks when the distance between the manikins is reduced.	
Qian and others [59]	Hospital wards	Experiment	A high concentration zone of exhaled droplet nuclei due to thermal stratification locking was observed in displacement ventilation. The application of displacement ventilation is not suggested in hospital wards.	
Li and others [60]	N/A	Review	Reviewed studies show that ventilation rate and airflow pattern is important to mitigate airborne infection.	Increase ventilation to dilute viral concentration and use appropriate airflow pattern to block the airborne transmission of viruses.
Morawska and others [61]	N/A	Survey	Adequate outdoor air and effective airflow pattern can reduce the airborne transmission of SARS-CoV-2.	
Nielsen and others [62]	Ventilated spaces	Experiment	Mixed ventilation can achieve a high ventilation rate and the appropriate layout of air supply outlets is needed to reduce infection risks.	

associated with mixed ventilation given the same ventilation rate. The number of viruses removed by displacement ventilation were twice that of mixed ventilation. However, displacement ventilation might facilitate the propagation and longevity of exhaled viruses in the air. Therefore, as reported in Ref. 58, it is not suitable for places characterized by a high density of people such as hospitals.

Personalized ventilation is an effective way to reduce the airborne transmission of SARS-CoV-2 and mitigate infection risks in indoor environments. Some novel personalized ventilation methods are suggested for virus control in indoor environments. As presented in Ref. 65, a personalized ventilation mode with circular movable plates could significantly reduce the concentration of pollutants around people and improve the quality of air inhaled. Xu and others [67] studied the role of personalized ventilation in preventing airborne transmission and found that infection could be reduced by mitigating the concentration of viruses in the suction area. Personalized ventilation can also assist other ventilation methods to remove viruses in a study by Cermak and Melikov [68]. The complete mixture of indoor air and exhaled air can be achieved by integrating personalized air supply and displacement ventilation, enabling the reduction of viral concentration. The indoor air quality can also be improved by combining personalized air supply and downward air supply as reported in Ref. 54.

2.3. *Airborne transmission in the special enclosed spaces*

Compared with buildings, this study considers aircraft, trains, subways, high-speed rail and buses as a special type of enclosed spaces. Zhu and others [69] noted that commuting constitutes about 7% of daily time, and public transportation is a primary mode of travel for many people. As reported by Associated Press [70], SARS-CoV-2 has been shown to spread in public transportation vehicles. Zhao and others [71] studied the correlation between travel by public transportation vehicles and the number of confirmed COVID-19 cases and obtained a significant correlation factor of 0.042 which indicates a strong relationship. Yi and others [72] analysed the contact mode between close contacts and confirmed cases and found that taking the same transportation could generate an infection rate of 11.91%.

Airborne transmission in these special enclosed spaces is the main mode of virus transmission. Infection risks are much higher than that in indoor environments, due to the higher passenger density, and ventilation is the only way to mitigate infection risks apart from using individual respiratory protection. Therefore, analysing the viral microenvironment in these enclosed spaces and limiting the airborne transmission of viruses through ventilation is of great significance. The following subsections will focus in more detail on individual transport modes.

2.3.1. Aircraft

Silverman and Gendrea [73] underlined the importance of understanding characteristics of virus spread in aircraft cabins as more than 2 billion people travel on commercial flights annually. The viral infection process on aircraft is characterized by long exposure time and high transmission speed. Air passengers spend extended periods in these enclosed spaces, sometimes even for more than 10 hours, which facilitates the propagation of infectious diseases. Gupta and others [74] found that the air transmission speed of viruses was high in the aircraft cabin, and droplets as well as aerosols exhaled by passengers occupying the front seats could be dispersed to up to seven rows back within four minutes. The exhaled air from passengers through coughing, breathing and talking was short-lived. Therefore, viral distribution and infection risks in aircraft cabins were uneven and varied over time as shown in a study by Yan and others [75] on airborne pollutant transport in an aircraft cabin.

Using ventilation to reduce infection risks in aircraft can be achieved by adopting two approaches. One is to increase the ventilation rate to dilute the viral concentration; another is to control the transmission of viruses to other occupied areas in the aircraft cabin. The deterministic model of tuberculosis survey in flight, carried out by Ko and others [76] showed that a doubled ventilation rate in an aircraft cabin could mitigate the infection ratio by 50%. Furthermore, the typical airflow pattern in the aircraft cabin is shown in Fig. 8 (a). The fresh air comes from air supply outlets located at the upper part of the aircraft cabin, and the airflow bypasses the luggage rack to reach occupied areas. Exhaust air inlets are located at the lower part, and discharge the contaminated air into the cargo compartment. This pattern can divide the airflow into several parts and block the spread of viruses.

2.3.2. Trains, subways and high-speed rail

Trains, subways and high-speed rail are globally prevalent modes of transportation for short and medium distances. They are also characterized by high passenger density, especially in cases of subways in urban areas. Infection risks in these transportation modes should not be neglected. Raghunathan and others [77] noted that in order to maintain stable pressure of the train cabins, the supply of outdoor air may be switched off when the external pressure changes too much, which greatly increases the risk of airborne transmission.

The available literature indicates that the virus content in trains is much higher than that on platforms, if proper ventilation systems are not available. Cha and others [78] studied the function of ventilation systems in trains and found that the viral concentration rose sharply when the ventilation system was closed, while the air quality was improved once the ventilation equipment was reopened. The study confirms that ventilation systems are crucial to controlling the airborne transmission of viruses in the train carriage environment. Zhang and others [79] studied four types of air exhausts in trains, and results showed that upper exhaust was more effective in reducing the spread of viruses. This could be attributed to the buoyancy and evaporation, which made viruses gather above the train cabin, and the upper exhaust removed viruses with a high efficiency. It should be note that the location of luggage rack can affect the propagation of viruses as the rack can hinder the upper vent from eliminating viruses located at the upper part of the train cabin. At the same time, the luggage also impacts the airflow pattern and traps some droplets. Typical airflow pattern in the high-speed rail cabin is presented in Fig. 8 (b).

2.3.3. Buses

Buses are a popular public transportation mode across the world. Many studies dedicated to the bus microenvironment have reported serious air quality problems inside, showing a higher concentration level of pollutants than that of the outdoor air as reported by Chan [80]. Therefore, it is necessary to develop and adopt appropriate control strategies to protect passengers from airborne transmission diseases.

Contrary to trains and aircraft, the number of passengers in buses is highly variable and not limited by the number of seats. CO_2 concentration is an effective indicator to evaluate the air quality in a bus, and the level can reach 10 times that of outdoor air when the bus is full of passengers as reported by Zhu and others [81]. Compared with the ventilation on high-speed rail and aircraft, buses have the exceptional edge in natural ventilation, as windows can be opened, but poor ventilation may result from the obstruction of crowding as presented in Ref. 81. Therefore, it is necessary to combine natural ventilation with mechanical ventilation via the self-contained air-conditioning system in the bus, and maximal outdoor air mode is required. It is worth noting that natural ventilation is acceptable if the outdoor air is satisfactory for thermal comfort. Air-conditioning systems should be used if the outdoor air is not suitable to be introduced directly, and it is essential to filtrate outdoor air. Air filtration and disinfection methods are recommended to reduce the risk of airborne transmission as recommended in Ref. 80. In terms of traditional ventilation modes, Ref. 69 shows that displacement ventilation is more effective than mixed ventilation in limiting the airborne transmission of viruses in a bus, and the effect can be doubled by combining displacement ventilation with air recirculation and the installation of high efficiency particulate air (HEPA) filters. A typical airflow pattern in a bus is shown in Fig. 8 (c). Fresh air is supplied through air supply outlets located at both sides of the ceiling, and exhaust air inlets are located in the back of bus. In addition, operable windows also play an important role in air exchange. The appropriate application of ventilation is a valid way to mitigate infection risks in buses.

For further comparison of airborne transmission in the special enclosed spaces, Table. 3 shows the virus transmission characteristics and airflow patterns of different vehicles.

Appropriate and effective operation of HVAC systems is crucial to preventing the spread of SARS-CoV-2. Therefore, HVAC-related guidelines, which will be presented in the Section 3, have been issued by various authorities and agencies around the world for pandemic prevention and control in response to COVID-19. Furthermore, how to balance the increase of energy consumption and the improvement of air quality caused by ventilation deserves further analysis to get insight of energy impacts of COVID-19 on HVAC systems.

3. Operation guidelines of HVAC systems

The main objective of a HVAC system is to maintain occupants' thermal comfort while minimizing energy consumption. The focal point is the trade-off between thermal comfort and energy conservation. However, it is confirmed that HVAC systems play a non-negligible role in the airborne transmission of SARS-CoV-2 based on the discussion presented in the Section 2.2, and the appropriate operation of HVAC systems can effectively mitigate infection risks. The role of HVAC systems in COVID-19 prevention has attracted attention from various institutions as reported in Ref. 21, and it is of great significance to issue relevant operation guidelines to instruct the operation and management of HVAC systems during the pandemic period.

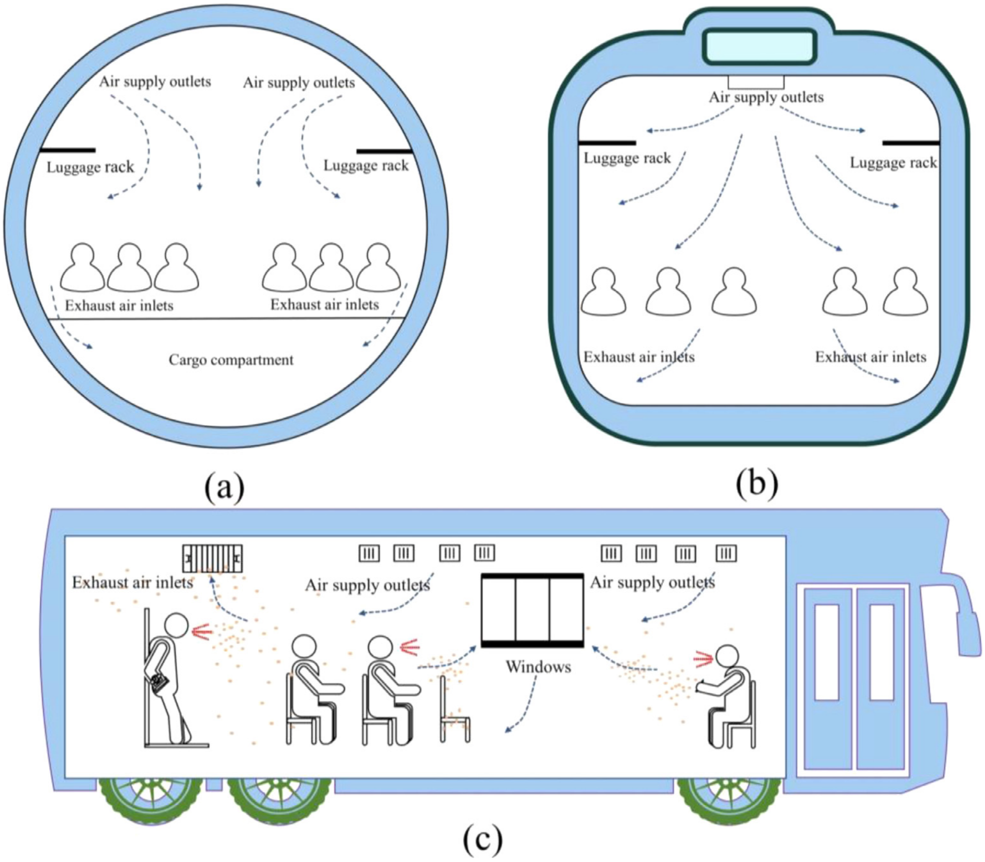


Fig. 8. Airborne transmission in the special enclosed spaces: (a) aircraft cabin, (b) high-speed rail cabin and (c) bus.

Table. 3
Virus transmission characteristics and airflow patterns of different vehicles.

Vehicles	Environmental characteristics	Virus transmission characteristics	Airflow pattern
Aircraft	Enclosed	Long exposure time and high transmission speed	Upper air supply and lower air exhaust
Trains, subways and high-speed rail	Enclosed, high personnel density	Long transmission distance	Upper air supply and lower air exhaust
Buses	Open, high personnel density and mobility	Crowding and congestion can affect the spread of viruses	Upper air supply and upper air exhaust

3.1. HVAC operation guidelines issued during the COVID-19 pandemic

Several countries all around the world have paid serious attention to the operation of HVAC systems. A selection of the main authorities, agencies and professional associations having policy, enforcement oversight and the establishment of standards and guidelines in the design and operation of HVAC systems mainly include:

- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE),
- Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA),
- European Centre for Disease Prevention and Control (ECDC),
- Canadian Committee on Indoor Air Quality (CCIAQ),
- Public Health Ontario (PHO),
- Architectural Society of China (ASC),
- Chinese Association of Refrigeration (CAR),
- National Health Commission of China (NHC),
- Society of Heating, Air-Conditioning and Sanitary Engineers in Japan (SHASE),
- Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE).

During the COVID-19 pandemic, ASC was the first to publish guidelines to promote appropriate use of HVAC systems, and since then various institutions have successively issued guidelines to provide practical advice on HVAC operation. A timeline of the issuance of various guidelines is shown in Fig. 9.

The guidelines and the corresponding authorities and organizations are listed in Table 4. The consecutive publication of guidelines reflects the concern on the unceasing advance of SARS-CoV-2, and the rate of updating guidelines is significant. More details regarding various guidelines can be found in Table 6. (Presented in the end of Section 3.)

It is clear from Table 4 above that a considerable number of documents have been issued. Therefore, it is important to seek commonalities for generalization and extract the common countermeasures as well as contradictions among various guidelines. Furthermore, the operation guidelines of HVAC systems during the normal times versus pandemic period should be compared. Comparisons of various HVAC system operation guidelines are presented in the following chapter. The comparisons and summary of these guidelines can provide references for the improving and updating of relevant documents and facilitate making full use of HVAC systems' potential in preventing the airborne transmission of SARS-CoV-2.

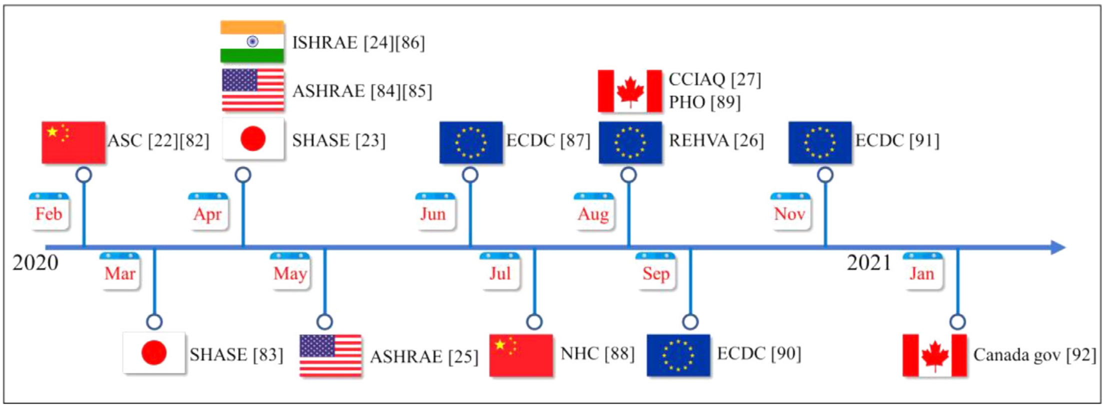


Fig. 9. Timeline of the issuance of various guidelines.

Table. 4
Guidelines issued during the pandemic.

Date	Association	Guideline
2020.2.5	ASC	Guidelines for office buildings to deal with “new coronavirus” operational management emergency measures [22]
2020.2.20	ASC	The Design Standard of Infectious Disease Emergency Medical Facilities for Novel Coronavirus (2019-nCov) Infected Pneumonia [82]
2020.3.30	SHASE	Q&A on Ventilation in the Control of SARS-CoV-2 Infection [83]
2020.4.8	SHASE	Operation of air-conditioning equipment and other facilities as SARS-CoV-2 infectious disease control 2020 [23]
2020.4.13	ISHRAE	ISHRAE COVID-19 Guidance Document for Air Conditioning and Ventilation [24]
2020.4.14	ASHRAE	ASHRAE Position Document on Infectious Aerosols [84]
2020.4.20	ASHRAE	ASHRAE Issues Statements on Relationship Between COVID-19 and HVAC in Buildings [85]
2020.4.21	ISHRAE	Start up and Operation of Air conditioning and Ventilation systems during Pandemic in Commercial and Industrial Workspaces [86]
2020.5.7	ASHRAE	Building Readiness [25]
2020.6.22	ECDC	Heating, ventilation and air-conditioning systems in the context of COVID-19 [87]
2020.7.20	NHC	Hygienic Specifications for Operation and Management of Air-conditioning Ventilation Systems in Office Buildings and Public Places during COVID-19 Pandemic [88]
2020.8.1	CCIAQ	Addressing COVID-19 in Buildings [27]
2020.8.3	REHVA	REHVA COVID-19 guidance document [26]
2020.8.31	PHO	COVID-19: Heating, Ventilation and Air Conditioning (HVAC) Systems in Buildings [89]
2020.9.24	ECDC	Guidelines for the implementation of non-pharmaceutical interventions against COVID-19 [90]
2020.11.10	ECDC	Heating, ventilation and air-conditioning systems in the context of COVID-19: first update [91]
2021.1	Canadian government	COVID-19: Guidance on indoor ventilation during the pandemic [92]

3.2. Comparison of guidelines from different institutions

In order to investigate various operation guidelines on HVAC systems and make full use of HVAC systems to prevent the airborne transmission of SARS-CoV-2, guidelines issued by institutions around the world are dissected and compared. Analysis has been conducted considering five aspects, namely, outdoor air and airflow pattern, temperature and relative humidity set-points, operation schedules, countermeasures for the specific spaces, and applications of auxiliary equipment. Key factors of HVAC operation to be discussed are illustrated in Fig. 10.

3.2.1. Guidelines for outdoor air and airflow pattern

It is well known that ventilation combined with appropriate airflow pattern can dilute indoor viral concentration, and this is an effective countermeasure to mitigate infection risks as recommended by ASHRAE in Ref. 84 and by Canadian government in Ref. 92. Furthermore, Correia and others [93], Amoatey and others [94] and Sun and Zhai [95] studied the impact of ventilation systems on the COVID-19 prevention and results indicate that ventilation was crucial to reducing airborne transmission. ASHRAE [96] proposes that the outdoor air volume should be increased to as much as the HVAC system can accommodate. In mild weather seasons, opening outdoor air dampers as high as 100% is recommended, but this recommendation is hard to accomplish in extreme weather conditions noted by Lawrence [97]. If increasing ventilation up to 100% outdoor air is impossible or impractical, limiting the number of people in the building by administrative measures is a feasible solution to increase the effective rate of ventilation for each person as recommended by the US EPA [98]. During the normal times, demand-controlled ventilation (DCV) systems are utilized to conserve energy by switching off ventilation systems based on CO_2 concentration. However, DCV systems should be disabled during the pandemic to guarantee indoor air quality. As for the air flow pattern, ASHRAE emphasizes that exhaust air inlets should not be arranged in pedestrian areas. In addition to mechanical ventilation, opening windows is a possible option to enhance the hourly air exchange rate when outside air quality and weather conditions are acceptable. Furthermore, ASHRAE points out

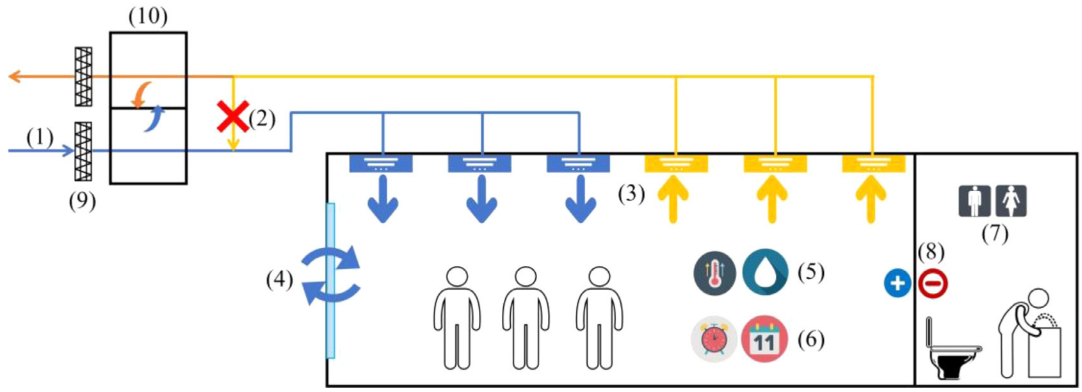


Fig. 10. Key factors of HVAC operation: (1) outdoor air; (2) air recirculation; (3) airflow pattern; (4) natural ventilation; (5) temperature and relative humidity; (6) operation schedule; (7) specific area; (8) pressure differential; (9) HEPA filter; (10) heat recovery device.

that the hourly air exchange rate should be three; this can reduce the concentration of airborne infectious particles by 95% as presented in Ref. 25.

ECDC claims that adequate ventilation of outdoor air should be provided for indoor spaces as presented in Ref. 91, and REHVA points out that air handling units (AHU) ought to be switched to 100% outdoor air without air recirculation as presented in Ref. 26. DCV systems controlled by CO_2 detectors for energy saving should be turned off during the COVID-19 pandemic, and indoor air quality should be prioritized over energy conservation. As for natural ventilation, occupants should open windows for 15 minutes when entering a room, especially when others have occupied the room earlier. In terms of airflow pattern, direct airflows should be diverted away from occupants in order to avoid the transmission of SARS-CoV-2. REHVA uses CO_2 as the indicator of indoor air quality, and the installation of CO_2 sensors is recommended in occupied zones. CO_2 sensors are able to warn occupants when CO_2 concentration exceeds 800 ppm, and facility managers can adequately monitor the operation of ventilation systems with the support of an indoor air quality sensor network.

CCIAQ confirms that HVAC systems should be inspected, cleaned, and confirmed as capable of maintaining enough airflow, and the supply of outdoor air should be maximized to avoid recirculation of contaminated air as presented in Ref. 27. In buildings without mechanical ventilation or air-conditioning, high-capacity air exchange ventilation systems should be installed as recommended by Ref. 89. Generally, ventilating indoor environments with fresh outdoor air is necessary, and increasing the outdoor air rate via HVAC systems as well as by opening windows can contribute to the dilution of air exhaled by occupants. DCV systems should be disabled to guarantee indoor air quality. PHO points out that the existing standard for the hourly air exchange rate was established during the normal times, and the explicit index should be further increased. The CO_2 level can serve as the indicator to justify whether outdoor air ventilation is adequate for occupants. In terms of airflow pattern, CCIAQ proposes that the layout of exhaust air inlets as well as air supply outlets should be checked, adjusted, corrected and optimized to guarantee the quantities of exhaust air and supply air. Appropriate airflow pattern is beneficial to eliminate dead zones of indoor air.

NHC suggests that sources of outdoor air should be checked before operating HVAC systems to avoid contamination as presented in Ref. 88. Outdoor air ratio of 100% and disabling air recirculation is recommended in medium-risk and high-risk regions, while in low-risk regions outdoor air systems should maximize the outdoor air volume and reduce air recirculation as much as possible. The balance of airflow in each area should be checked to prevent cross contamination when the maximal outdoor air mode is implemented. The antifreeze protection function should be inspected to ensure the operation of ventilation systems in the cold and severe cold zone. The location of air supply outlets and exhaust air inlets should be kept a distance apart to avoid the airflow short-circuiting, and HVAC systems should be switched off when it is impossible to physically adjust the location of outlets or inlets. Windows and doors should be opened to enhance airflow when an indoor space is crowded.

SHASE proposes that the ratio of outdoor air should be close to 100% and air recirculation should be disabled as presented in Ref. 23. Mechanical and natural ventilation should be combined to obtain optimal indoor air quality. In some high-rise buildings, it may be difficult to open windows and therefore mechanical ventilation systems can play a dominant role in air exchange. It is recommended to set the hourly air exchange rate to be three, which enables reduction of virus occurrence by 95%. As for the airflow pattern, the air supply outlets and exhaust air inlets should be kept a distance apart to avoid the airflow short-circuiting. In addition, the blockage of air supply outlets and exhaust air inlets should be eliminated.

ISHRAE claims that providing adequate ventilation is important, and mechanical ventilation systems as well as air-conditioning systems can outperform opening windows because they can use filtration technologies to improve outdoor air quality as presented in Ref. 24. However, for buildings without mechanical ventilation systems, occupants should open windows regularly to introduce outdoor air into rooms. A minimum outdoor air volume of 8.5 m^3/(h•person) is recommended to guarantee sufficient indoor air quality.

According to the guidelines above, it is clear that all the guidelines highlight the importance of introducing outdoor air into indoor spaces as much as possible, and minimizing air recirculation in HVAC systems. Mechanical and natural ventilation should be utilized to full capacity to improve indoor air quality and mitigate the airborne transmission of SARS-CoV-2. Disabling DCV systems is mentioned by ASHRAE, REHVA and CCIAQ to prioritize indoor air quality rather than energy conservation during the COVID-19 pandemic. Furthermore, REHVA and PHO use CO_2 as the indicator to monitor the operation efficiency of ventilation systems. ASHRAE and SHASE recommend setting the hourly air exchange rate to be three, which is enough to eliminate indoor virus occurrence by 95%, while other institutions have not determined the rational index of hourly air exchange rate. In terms of the airflow pattern, various guidelines put forward measures from different perspectives to promote indoor airflow. ASHRAE, CCIAQ, NHC and SHASE propose that the layout of air supply outlets and exhaust air inlets should be designed to improve the dilution effect of airflow as well as to avoid short-circuiting and dead zones of airflow, while REHVA expresses that direct airflows should be diverted away from occupants.

3.2.2. Guidelines for temperature and relative humidity set-points

As illustrated in Section 2.1, the viability of SARS-CoV-2 is affected by indoor air temperature and relative humidity. Dehbandi and others

[99], Dietz and others [100], Wang and others [101] and Derby and others [102] investigated impacts of indoor temperature and relative humidity on SARS-CoV-2 and results indicate that appropriate set-points are necessary to deactivate viruses. ASHRAE proposes that indoor relative humidity be set between 40% to 60%, and temperature between 18 °C to 26 °C is normally appropriate to operate HVAC systems in winter and summer. The optimal set-points to deactivate SARS-CoV-2 are not presented in Ref. 25.

REHVA offers a different claim, namely that changing the temperature and relative humidity set-point is not an effective option as SARS-CoV-2 can easily resist indoor environment changes within the occupants' thermal comfort zone. SARS-CoV-2 becomes susceptible to high relative humidity over 80%, but this (as written earlier) is difficult to achieve considering indoor thermal comfort as presented in Ref. 26. REHVA also points out that SARS-CoV-2 is found to be viable for 14 days at 4 °C, for 1 day at 37 °C and for 30 minutes at 56 °C, but it is obvious that the temperature above 37 °C is unrealistic in the case of indoor environments.

CCIAQ expresses that a relative humidity between 40% to 60% is recommended, given that the relative humidity below 40% may increase vulnerability to infection, while relative humidity over 60% may result in water condensation as well as cold walls, which will cause mildew in buildings as presented in Ref. 27.

ASC suggests that the temperature set-points of supply air should increase and decrease in the winter and summer, respectively, as presented in Ref. 22. Increasing the outdoor air volume is detrimental to indoor thermal comfort, therefore it is necessary to adjust temperature set-points so that outdoor air can undertake more heating and cooling load during the pandemic. In terms of the cold and severe cold zone, it is worth noting that indoor temperature should be above 5 °C to 8 °C to avoid frost damage of indoor equipment.

SHASE claims that the resistance of nasal mucosal is weakened in environments with low relative humidity, although it is not specified whether high temperature and relative humidity can reduce the viability of SARS-CoV-2 as presented in Ref. 23. SHASE proposes the optimal range of indoor temperature and relative humidity at 17 °C to 28 °C and 40% to 70%, respectively. ISHRAE proposes that room temperature should be set between 24 °C to 30 °C. Temperature should be closer to 24 °C in humid climates and 30 °C in dry climates as presented in Ref. 24. As for humidity, a range between 40% to 70% is recommended to reduce impacts from SARS-CoV-2 while maintaining indoor thermal comfort.

It can be concluded that various institutions' guidelines regarding temperature and relative humidity set-points are different. ASHRAE and CCIAQ agree that indoor relative humidity be set between 40% to 60%. By contrast, REHVA claims that the temperature and relative humidity set-points should be the same as during the normal times because the impact of temperature and relative humidity on viruses is limited. According to ASC, temperature set-points are adjustable to let outdoor air undertake more heating and cooling load, and the optimal value of temperature and relative humidity to deactivate SARS-CoV-2 requires further study. SHASE and ISHRAE put forward their own ranges to reduce virus viability. The temperature and relative humidity ranges recommended by ASHRAE, ISHRAE and SHASE are presented in Fig. 11 (a).

3.2.3. Guidelines for HVAC system operation schedules

During the COVID-19 pandemic, it is necessary to extend the operation schedules of HVAC systems in order to meet the relevant requirements of pandemic spread prevention. According to guidelines regarding HVAC system operation schedules, extra running hours are recommended, and the difference mainly focuses on time horizons. Fig. 11 (b) presents operation schedules of various guidelines, and more details can be found in Table 6. The adjustment of operation schedules effectively improves indoor air quality before occupants enter a building, and the stale indoor air can be exhausted thoroughly by extending operation hours. However, the extended operation schedules lead to extra energy consumption, and therefore HVAC systems should operate at lower load ratio for energy conservation when the building is unoccupied.

3.2.4. Countermeasures for the specific spaces

A building tends to have various types of zones, including some special spaces such as toilets and kitchens. As for hospitals, clean rooms and isolation wards are representative spaces. These spaces usually have special requirements for ventilation and pressure differential. Guidelines have presented several suggestions to ensure the safe use of these specific spaces during the COVID-19 pandemic.

ASHRAE proposes that increased outdoor air volume may create problems for the pressure differential if the exhaust and relief air systems operate as designed as presented in Ref. 25. During the pandemic, exhaust air systems should be evaluated and accommodated to keep negative pressure in specialized spaces such as bathrooms, process areas, custodial areas and commercial kitchens.

REHVA points out that ventilation systems of toilets should operate 24 hours per day, and windows in toilets should not be opened to avoid cross contamination as presented in Ref. 26. Moreover, occupants are instructed to flush toilets with lids closed, and water seals should be checked every three weeks to prevent potential risks of SARS-CoV-2 transmission.

CCIAQ suggests installing special exhaust systems in high-risk spaces such as washrooms and rooms containing confirmed cases, and exhaust systems should operate 24 hours per day, as recommended by Ref. 27.

ASC recommends regularly disinfecting critical areas such as kitchens as well as toilets, and the water seals in toilets should be checked as presented in Ref. 22. Exhaust air systems in toilets and hot water rooms as well as ventilation systems in underground garages should operate 24 hours per day. Furthermore, the location of exhaust air inlets in toilets should be checked and contaminated airflows should be prevented from being diverted to other areas. The pressure of toilets and disposal rooms should be negative.

SHASE confirms that toilets, bathrooms and kitchens should be controlled with negative pressure, and the airflow route should run from clean areas to polluted areas, as recommended by Ref. 23. ISHRAE emphasizes that the exhaust airflow from toilets to other occupied zones is prohibited, and exhaust fans in toilets and kitchens should be kept in operational mode, as recommended by Ref. 24. Furthermore, the pressure of isolation wards should be negative and the hourly air exchange rate of wards containing confirmed cases should be twelve.

In terms of the specific spaces, countermeasures recommended by various guidelines are compared in Table 6. It can be concluded that the special areas mainly include toilets, kitchens and wards. Countermeasures involve maintaining negative pressure, flushing toilets with lids closed, and checking water seals regularly. Exhaust air systems in the specific spaces should be kept in operational mode, and contaminated airflows should be prevented from being diverted to other areas.

3.2.5. Applications of auxiliary equipment

Auxiliary equipment mainly includes air filters, ultraviolet germicidal irradiation (UVGI) systems and portable air cleaners. Auxiliary equipment can serve as effective complementary measures in diluting SARS-CoV-2 and reducing airborne transmission, especially when increasing outdoor air volume is impossible or when the risk level of the area is medium or high.

ASHRAE recommends using UVGI systems or filters with a minimum efficiency reporting value (MERV) of 13, when there are significant energy conservation requirements and only minimum outdoor air is available as presented in Ref. 96. Upgrading filters to a high level of MERV-13 or MERV-14 can effectively mitigate the aerosol transmission of SARS-CoV-2. However, it is worth noting that the air pressure requirement of air supply fans will increase with the introduction of high-level filters, and it is necessary to ensure that HVAC systems are still capable of meeting the requirements of fresh air demand and pressure differential

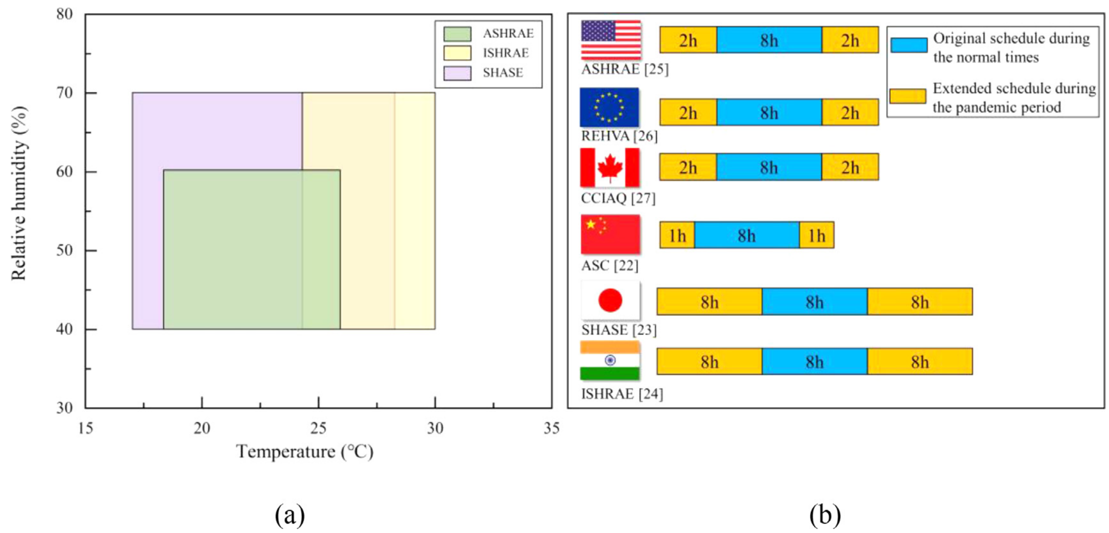


Fig. 11. Ranges of temperature and relative humidity (a) and operation schedules (b) recommended by various guidelines.

after upgrading filters. ASHRAE adds that a heat recovery device can be utilized when the leakage is acceptable.

REHVA claims that changing outdoor air filters is unnecessary, because modern ventilation systems have been equipped with high-class filters of F7 or F8, which is sufficient to filter particulates from outdoor air as presented in Ref. 26. Air cleaners and UVGI systems can be applied to mitigate the spread of SARS-CoV-2 in the short term, while the improvement of ventilation systems is necessary in the long run. Regarding the maintenance of filters and ducts, replacing air filters and cleaning ducts according to normal schedules is enough, and extra cleaning is unnecessary. It is worth highlighting that common measures for respiratory protection should be taken during replacement and maintenance work. REHVA indicates that heat recovery device installation is justified for a ventilation system for leakage is below 5%.

CCIAQ recommends taking advantage of stand-alone air filtration, humidification and dehumidification equipment according to increased ventilation rates and outdoor air conditions, as recommended by Ref. 27. The level of filters should be upgraded to MERV-13 or better, and HEPA filters can be applied as well. In addition to the above equipment, UVGI systems can be used in healthcare to purify contaminated air. With regard to heat recovery devices, cross contamination between outdoor air and exhaust air should be avoided.

ASC proposes that air filters be upgraded to HEPA filters, and portable air cleaners can be used during the daytime as presented in Ref. 22. UVGI systems are not recommended for installation in HVAC systems without consulting relevant medical experts. The cleaning, disinfecting and replacement of air filters in air supply outlets, exhaust air inlets and ducts should be done every week. As for heat recovery devices, rotary heat exchangers should be avoided while indirect heat exchangers can be adopted.

SHASE guidelines state that medium-efficiency filters can be adopted in offices, and HEPA filters can be applied in operating theatres as presented in Ref. 23. Portable air cleaners are efficient as auxiliary equipment. Maintenance of air filters can be executed according to normal schedules when HVAC systems operate in 100% outdoor air mode. The pressure differential of air filters should be carefully inspected to avoid blockage when HVAC systems operate with air recirculation. SHASE also recommends that heat recovery devices can be utilized for leakage is below 5%.

ISHRAE proposes that the level of air filters should be upgraded to MERV-13, and the capacity of fans and motors should be able to adapt to increased pressure drops as presented in Ref. 24. UVGI systems and HEPA filters are recommended to dispose of stale air, and portable air cleaners should be selected according to room size. HVAC equipment should be cleaned regularly. Rotary heat exchangers are supposed to be disabled in order to prevent cross contamination between outdoor air and exhaust air.

Regarding auxiliary equipment applications, all the guidelines agree that the relevant equipment used be efficient to mitigate the transmission of SARS-CoV-2. Recommendations of auxiliary equipment from various guidelines are listed in Table 5.

3.3. Comparison of guidelines during the normal times versus pandemic period

In this section, the operation guidelines applying in China during the normal times and pandemic period are compared. Guidelines published during the normal times mainly include “Design code for heating, ventilation and air-conditioning of civil buildings” [103] and “Code for design of general hospital” [104] issued by the Ministry of Housing and Urban-Rural Development of the People’s Republic of China (MOHURD) in 2012 and 2014, respectively. In addition, “Hygienic indicators and limits for public places” [105] was issued by Standardization Administration of the People’s Republic of China (SAC) in 2019. The comparison focuses on requirements regarding outdoor air, return air and exhaust air during the normal times and pandemic period, and the process of air filtration during the pandemic is illustrated in Fig. 12.

3.3.1. Comparison of outdoor air requirements

With regard to the filtration of outdoor air, guidelines during the normal times propose that outdoor air should be cleaned firstly by a coarse filter and secondly by a medium-efficiency filter as presented in Ref. 104. While guidelines during a pandemic period recommend higher requirements, namely that filters be upgraded to HEPA filters, and outdoor air be cleaned firstly by a coarse filter, secondly by a medium-efficiency filter and finally by a HEPA filter.

3.3.2. Comparison of return air requirements

During the normal times, return air is usually used for energy conservation in HVAC systems. However, during a pandemic, the use of return air is minimized to create a healthy indoor environment and to reduce infection risks. In the normal times, return air should be purified by medium-efficiency filters which are required to have the microorganism pass rate below 10% and the particulate matter pass rate below 5% as presented in Ref. 104. While during a pandemic period, HEPA filters and sterilization instruments are required in return air systems.

Table. 5
Recommendations of auxiliary equipment.

	ASHRAE	REHVA	CCIAQ	ASC	SHASE	ISHRAE
MERV-13 air filter	√	√	√	√	√	√
HEPA filter	√	√	√	√	√	√
Air cleaner	√	√	√	√	√	√
UVGI system	√	√	√	×	√	√
Rotary heat exchanger	√	√	√	×	√	×

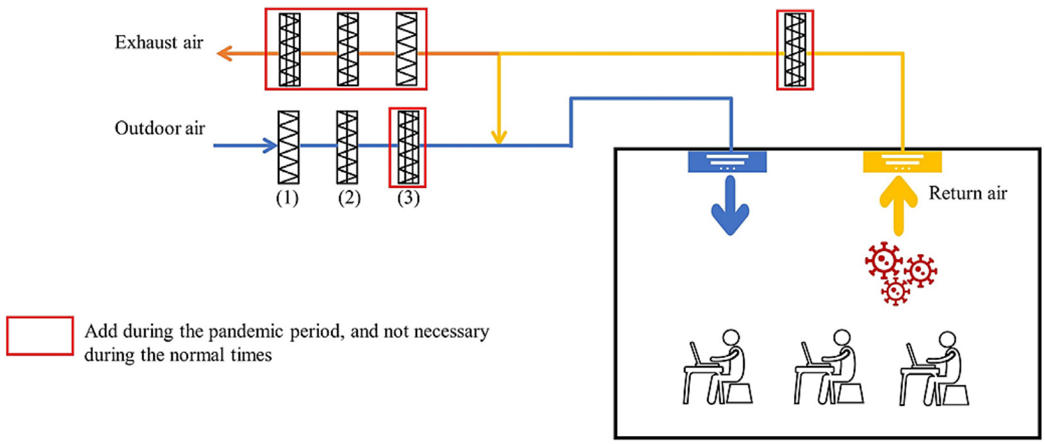


Fig. 12. Air filtration during the pandemic: (1) coarse filter; (2) medium-efficiency filter; (3) HEPA filter.

3.3.3. Comparison of exhaust air requirements

As for exhaust air filtration, during the normal times, guidelines relating to medical institutions in Ref. 104 propose that exhaust air should be cleaned in the following order: coarse filter, medium-efficiency filter and HEPA filter. By contrast, during a pandemic period, guidelines stipulate that filters for exhaust air in public buildings should be upgraded to HEPA filters, and the flow direction of exhaust air should be appropriately designed and prevent contaminated airflows from being diverted to other occupied areas.

Table 6 presents a comparison of guidelines issued by various institutions. This comparison indicates that there are considerable variations in HVAC system operation due to the COVID-19 pandemic. Operation variations of HVAC systems provided in these guidelines are bound to have a significant impact on energy consumption. Therefore, quantitative energy impacts of COVID-19 on HVAC systems are discussed and analysed in the Section 4.

4. Impacts of HVAC system operation on energy consumption

4.1. Impact factors of HVAC system operation on energy consumption

According to the discussion presented in the Section 3.2, it can be concluded that increasing the share of outdoor air in the ventilation supply air, introducing auxiliary equipment and extending the HVAC system operating schedules are the main recommended pandemic prevention and control measures. These recommended measures will impact HVAC system energy consumption. Generally speaking, increasing outdoor air volume, adding HEPA filters and UVGI systems, and extending the HVAC operating schedules can, to different degrees, increase HVAC system energy consumption. To alleviate the pressure of sharply increased HVAC system energy consumption caused by the pandemic, installing heat recovery devices is suggested. A quantitative illustration of the impacts of the above measures on HVAC system energy consumption is provided in the following sections to analyse energy impacts of COVID-19 on HVAC systems.

4.1.1. Outdoor air volume

During the normal times, intake of outdoor air aims to maintain indoor hygiene, to replenish the amount of air consumed by indoor combustion equipment, to replenish the exhaust volume of local ventilation systems, and to maintain positive pressure. However, during the pandemic period, air quality takes priority in order to mitigate infection risks. Poor ventilation may lead to a high infection risk; this has been confirmed in many cases from Ref. 12. Therefore, all the guidelines issued by various institutions emphasize that HVAC systems should rely on outdoor air to prevent the spread of SARS-CoV-2 during the pandemic period. Meanwhile, the use of air recirculation should be reduced or even stopped to avoid cross infection caused by airborne transmission according to the guidelines provided in the Section 3.2.1.

From the above discussion, the benefits of increasing the share of outdoor air are clear. Fisk and others [106] studied the possibility of increasing ventilation rate and improving work efficiency in offices, and results showed that increasing the minimum ventilation rate brought obvious benefits. At the same time, improving the ventilation rate can also reduce the symptoms of absenteeism as well as sick building syndrome (SBS), and improve the attendance rate of employees as reported by David and others [107]. However, the energy consumption caused by outdoor air processing is the bulk of air-conditioning load, and increased outdoor air volume leads to a substantial rise in HVAC system energy consumption. Generally speaking, outdoor air introduced from outside usually needs to be filtered, heated or cooled, dehumidified or humidified before supplying it into indoor rooms. This undoubtedly increases the load on equipment and the energy consumption of HVAC systems. The variations in heating and cooling demand caused by ventilation also affect energy consumption. Fig. 13 shows the variations in building heating and cooling demand with ventilation rate. The figure indicates that heating demand increases by 50% or more when the ventilation rate increases from 0 to 50 $m^3/(h•person)$, and the energy consumption increases proportionally. Although increased ventilation rate leads to decreased cooling demand, increased heating and power demand for driving ventilation fans eventually increases total energy consumption as presented in Ref. 28. Therefore, it can be concluded that increased outdoor air volume specified in guidelines regarding HVAC systems dur-

Table 6
Comparison of guidelines issued by various institutions.

	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Outdoor air and airflow pattern	1. Increase outdoor air volume as much as possible. 2. Disable DCV systems. 3. Arrange exhaust air inlets away from pedestrian areas. 4. Open windows. 5. Hourly air exchange rate of three is recommended.	1. Switch AHUs to 100% outdoor air. 2. Disable DCV systems. 3. Open windows for 15 minutes before entering a room. 4. Direct airflows should be diverted away from occupants. 5. Use CO_2 as indicator of indoor air quality.	1. Inspect HVAC systems before use. 2. Maximize outdoor air volume and avoid air recirculation. 3. Disable DCV systems. 4. Use CO_2 as indicator of indoor air quality. 5. Optimize layout of exhaust air inlets as well as air supply outlets, and eliminate dead zones.	1. Check sources of outdoor air. 2. Maximize outdoor air volume and reduce air recirculation. 3. Check balance of airflow in each area. 4. Inspect function of antifreeze protection of outdoor air systems in the cold and severe cold zone. 5. Avoid airflow short-circuiting. 6. Open windows and doors.	1. Outdoor air ratio of 100j% is recommended. 2. Hourly air exchange rate of three is recommended. 3. Avoid airflow short-circuiting. 4. Eliminate blockage of air supply outlets and exhaust air inlets.	1. Provide adequate ventilation. 2. Open windows regularly for buildings without mechanical ventilation systems. 3. A minimum outdoor air volume of 8.5 $m^3/(h{\bullet}person)$ is recommended.
	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Temperature and relative humidity set-points	1. Relative humidity should be set between 40% to 60%. 2. Temperature should be set between 18 °C to 26 °C in summer and winter, respectively.	1. Effects of temperature and relative humidity are limited.	1. Relative humidity should be set between 40% to 60%.	1. Increase and decrease temperature of supply air in winter and summer, respectively.	1. Relative humidity should be set between 40% to 70%. 2. Temperature should be set between 17 °C to 28 °C in summer and winter, respectively.	1. Relative humidity should be set between 40% to 70%. 2. Temperature should be set between 24 °C to 30 ºC in summer and winter, respectively.
Operation schedules of HVAC systems	1. HVAC systems operate extra 2 hours before and after a building is occupied. 2. Ventilation systems and relevant exhaust systems should operate for cleaning crews or maintenance workers.	1. Ventilation systems should work at a nominal speed at least 2 hours before the building opening and set to a lower speed 2 hours after the building usage time. 2. Ventilation systems should run at nights and weekends at a lower speed.	1. Ventilation systems operate extra 2 hours before and after a building is occupied.	1. Ventilation systems operate extra 1 hour before and after a building is occupied.	1. Ventilation systems operating around the clock is suggested.	1. HVAC systems should operate around the clock. 2. Air recirculation mode should be switched on during weekends and holidays.
	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Countermeasures for the specific spaces	1. Exhaust air systems should be accommodated to keep negative pressure for bathrooms, process areas, custodial areas and commercial kitchens.	1. Ventilation systems of toilets should operate 24 hours per day, and windows in toilets should not be opened. 2. Occupants should flush toilets with lids closed. 3. Water seals should be checked every three weeks.	1. Install special exhaust systems in high-risk spaces such as washrooms and rooms containing confirmed cases, and exhaust systems should operate 24 hours per day.	1. Regularly disinfect critical areas such as kitchens and toilets. 2. Regularly check water seals. 3. Exhaust air systems in toilets and hot water rooms as well as ventilation systems of underground garages should operate 24 hours per day. 4. Pressure of toilets and disposal rooms should be negative.	1. Toilets, bathrooms and kitchens should be controlled with negative pressure. 2. Airflow route should run from clean areas to polluted areas.	1. Exhaust airflow being diverted from toilets to other occupied zones is prohibited. 2. Exhaust fans in toilets and kitchens should be kept in operational mode. 3. Pressure of isolation wards should be negative and the hourly air exchange rate of wards containing confirmed cases should be twelve.
	ASHRAE	REHVA, ECDC	CCIAQ, PHO	ASC, NHC	SHASE	ISHRAE
Application of auxiliary equipment	1. MERV-13 filters and UVGI systems are recommended. 2. Make sure HVAC systems are capable of meeting indoor thermal comfort requirements and pressure differential after upgrading filters. 3. Heat recovery devices can be utilized for leakage is acceptable.	1. Changing outdoor air filters is not necessary. 2. Air cleaners and UVGI systems can be applied in the short term. 3. Replacing air filters and cleaning ducts as normal schedules is enough. 4. Common measures for respiratory protection should be taken during replacement and maintenance work. 5. Heat recovery devices can be utilized for leakage is below 5%.	1. Take advantage of stand-alone air filtration, humidification and dehumidification equipment according to increased ventilation rates and outdoor air conditions. 2. Filters should be upgraded to MERV-13 or better, and HEPA filters can be applied. 3. UVGI systems can be used in healthcare to purify contaminated air. 4. Cross contamination between outdoor air and exhaust air should be avoided with the application of heat recovery devices.	1. Air filters can be upgraded to HEPA filters, and portable air cleaners can be used. 2. UVGI systems are not recommended for installation in HVAC systems. 3. Cleaning, disinfecting and replacement of air filters in air supply outlets, exhaust air inlets and ducts should be done every week. 4. Rotary heat exchangers should not be applied.	1. Medium-efficiency filters can be adopted in offices, and HEPA filters can be applied in operating theatres. 2. Portable air cleaners are efficient. 3. Maintenance of air filters can be executed according to normal schedules when HVAC systems operate in 100% outdoor air mode. 4. Heat recovery devices can be utilized for leakage is below 5%.	1. Air filters should be upgraded to MERV-13 and the capacity of fans and motors should be able to adapt to increased pressure drops. 2. UVGI systems and HEPA filters are recommended. 3. Portable air cleaners should be selected according to room size. 4. Rotary heat exchangers should not be applied.

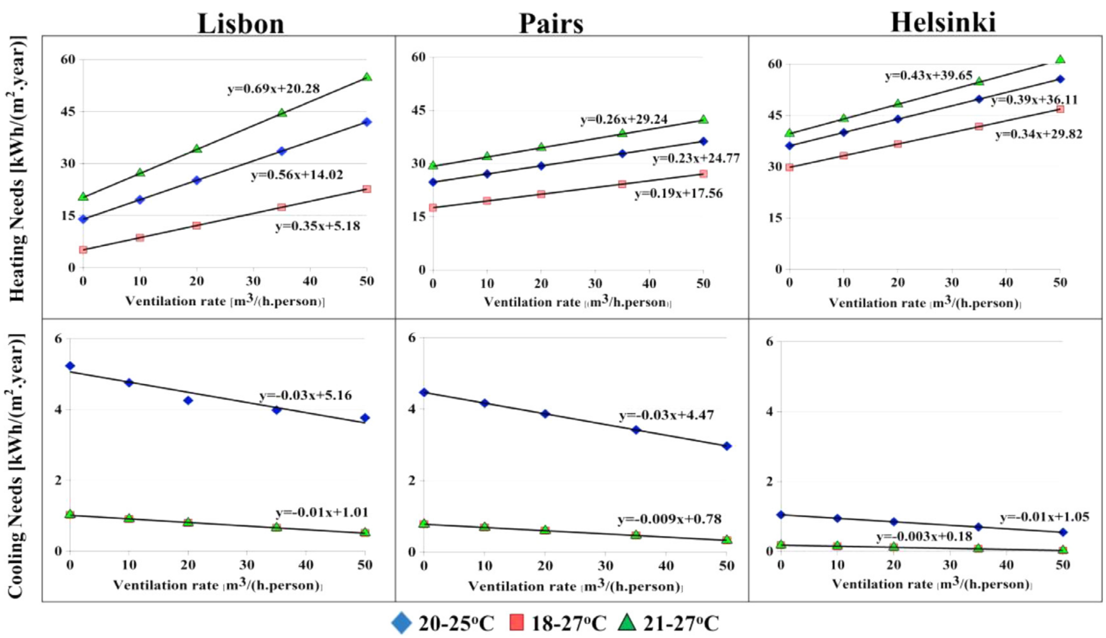


Fig. 13. Building cooling and heating demand as a function of ventilation rate. (Reproduced from Ref. 28.)

ing the COVID-19 pandemic will cause a significant increase in energy consumption.

Therefore, numerous scholars have focused their attention on the impact of ventilation and outdoor air volume on HVAC system energy consumption. According to the US EPA, increasing the minimum outdoor air rate from 2.5 L/(s•person) to 10 L/(s•person) will increase the operation costs of HVAC systems by 2 to 10% as presented in Ref. 29. Study presented in Ref. 30 found that the energy use intensity would increase by 150% if the ventilation rate were raised from 0 to 200%. Conversely, reducing the supply of outdoor air leads to a decrease in energy consumption. Study presented in Ref. 31 analysed the annual energy consumption of HVAC systems in five different cities located in Turkey. The results indicate that the energy consumption could be reduced significantly by decreasing outdoor air volume. In their study, Wang and others [108] adjusted the outdoor air supply rate according to the occupancy rate in buildings, and could achieve energy savings of 44.26% on weekdays and 55.5% on weekends. Increasing the hourly air exchange rate will lead to a change in energy consumption, and the principle is the same when increasing outdoor air volume. Study presented in Ref. 32 compared the energy consumption of HVAC systems in 14 Chinese cities when the hourly air exchange rate was increased. The results indicate that the relative increase of annual energy consumption for heating were raised by 103% to 264.5%.

It can be seen that increasing outdoor air volume is beneficial to reducing airborne transmissions and mitigating infection risks, but can lead to a sharp rise in the energy consumption of HVAC systems. Therefore, it is necessary to introduce some energy-saving equipment and adopt improvement measures to reduce energy consumption of HVAC systems during a pandemic period.

4.1.2. Applications of auxiliary equipment

The COVID-19 pandemic has posed new challenges for HVAC systems. To prevent SARS-CoV-2 from spreading in enclosed environments, many institutions have issued updated operation guidelines regarding HVAC systems. According to the discussion presented in the previous section, it can be concluded that the application of auxiliary equipment such as HEPA filters and UVGI systems can reduce the risk of virus transmission through HVAC systems, but this also impacts energy consumption.

4.1.2.1. HEPA filters. Most of the HVAC guidelines state that HEPA filters are effective equipment to reduce airborne transmission of SARS-CoV-2 according to the guidelines provided in the Section 3.2.5. The filter medium of a HEPA filter consists of randomly arranged fibres that intercept particles passing through the filter by diffusion, interception and inertial impact as presented in Ref. 96. The schematic of the filtration mechanisms is shown in Fig. 14 as reported by Christopherson and others [109]. According to Schentag and others [110], a HEPA filter can remove 99.7% of particles from 0.15 to 0.2 microns, and its prevention and control performance has been confirmed during the SARS period.

However, the application of HEPA filters increases the pressure drop of ventilation fans, and with the accumulation of particulate matter in the filter, the pressure drops even further, which results in a high increase of HVAC system energy consumption as presented in Ref. 33. Study results in Ref. 34 indicate that the introduction of HEPA filters resulted in 1.2 times higher energy consumption. Grainge [111] reported that the resistive characteristics of HEPA filters are mainly related to the material used and their structure. In terms of filtration, numerous researchers are working on developing media with higher filtration efficiency and lower pressure drop. The dust-carrying performance and pressure drops of different media were studied by Zhang and others [112], who found that the pressure drop of a H14 PTFE medium was about 140 to 370 Pa when the load dust mass is 0 to 6 g/m^2, while it was about 220 to 370 Pa for a H14 glass fibre. The energy consumption of H14 glass fibre was about 1.57 times that of H14 PTFE. The pressure drop of fluidized bed filters (made of carbon nanotubes) and packed bed filters was investigated by Wang and others [113], who found that, the pressure drop of a packed bed filter with a bed height of 8.1 to 17.4 cm was 506 to 1063 Pa, while the pressure drop of a fluidized bed filter was 88 to 167 Pa. The above findings show that the energy consumption of a packed bed filter was 5 to 7 times that of a fluidized bed filter. An ES air filter having its surface covered with antimicrobial nanoparticles was studied by Sim and others [114] using aerosol technology. The pressure drop of the antimicrobial filter was 7.35 to 25.2 Pa when the airflow velocity on the working face increased from 13.3 cm/s to 40 cm/s, while the pressure drop was 4.7 to 13.72 Pa for the original filter. The energy consumption of the antimicrobial filter was about 1.84 times that of the original filter. A multifunctional filter using polyacrylonitrile nanofibers synthesized by green electrospinning embedded in commercial P25 and/or TiO_2 bead fillers was proposed by Chen and

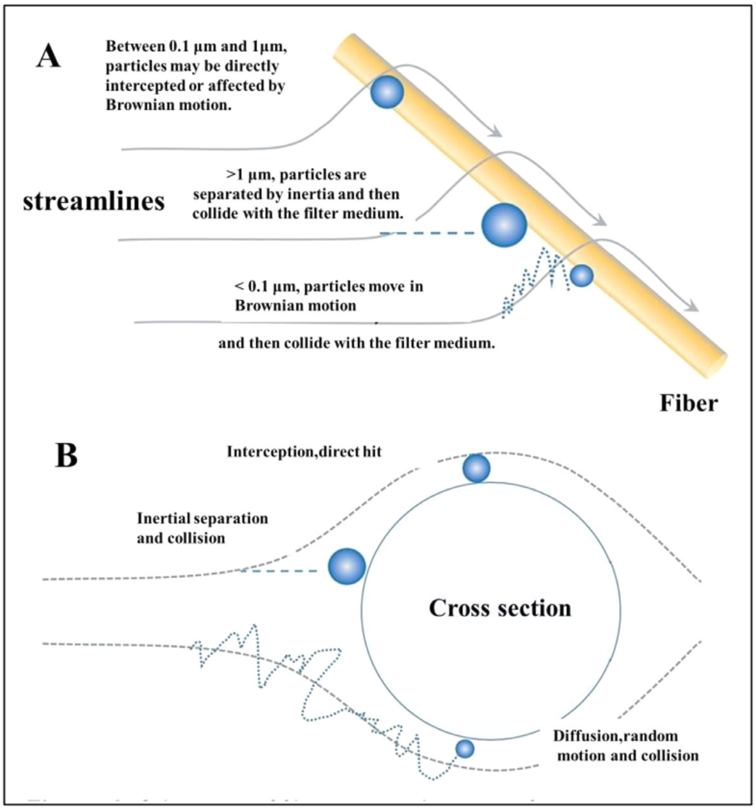


Fig. 14. Schematic of filtration mechanisms of impaction, interception and diffusion. (Modified from Ref. 109.)

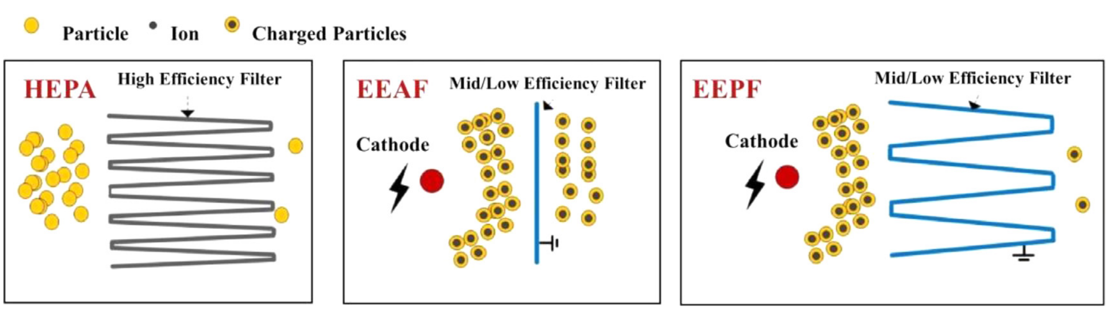


Fig. 15. Principle description of HEPA, EEAF and EEPF. (Reproduced from Ref. 121.)

others [115]. The filter possessed a filtration efficiency of 96.75% with a pressure drop of 88 Pa. A new multifunctional air filter material was produced by Wang and others [116] by adding β-cyclodextrin to electrospinning membrane, boasting a filtration efficiency of 99% and low pressure drop of 45 Pa. The suitability of coated foam as HEPA aerosol filter was investigated by Innocentini and others [117]. Layered media containing nanowire maintained the low pressure drop level of the foam substrate; the pressure drop of the coating foam and the HEPA filter was 0.5 to 30 Pa and 250 Pa, respectively, when the filtration speed was 5 cm/s. It can be concluded that filters with different filtration media have various pressure drop values, which results in different impacts on the energy consumption of HVAC systems. The impacts of filter medium on pressure drop are presented in Table 7.

Table. 7
Impacts of filter medium on pressure drop.

Filter/medium type	Pressure drop
H14 PTFE	140 - 370Pa [112]
H14 glass fibre	220 - 370Pa [112]
Fluidized bed filter	88 - 167Pa [113]
Packed bed filter	506 - 1063Pa [113]
ES air filter	7 - 25Pa [114]
Polyacrylonitrile nanofibers	88 Pa [115]
β-cyclodextrin with electrospinning membrane	45 Pa [116]
Coated foam	1 - 30Pa [117]

Filter structure is another factor affecting HVAC system energy consumption. To study the optimal air filtration solution for Vancouver Airport in Canada, Montgomery and others [118] compared 30 different filters from 6 manufacturers. The results indicate that the V-filter was the most energy-efficient, with a filtration efficiency of 99.98%, and the lowest pressure drop for fixed air volume air-conditioning systems. Zhang and others [119] conducted a longitudinal comparative study on the airflow resistance and energy consumption of air filters with different structures in aircraft passenger cabins. At a certain rated air volume, the pressure drop of V-shaped, cylinder and plate filters were 336 Pa, 136 Pa and 308 Pa respectively, and their energy consumption over the whole life cycle was 2622 kWh, 782 kWh and 1222 kWh. Suksuntornsiri and others [120] analysed the effects of additional high-efficiency filters (the filter sheet area can be manually adjusted) on air-conditioning units in the Thai climate. Energy consumption of the system increased by 15% and 11% per hour when 100% and 50% filtration was used, respectively.

Feng and others [121] developed an electrostatic reinforced pleated air filter (EEPF); the principles of three kinds of filters are shown in Fig.15. The energy consumption of the EEPF was about 40 W/(m^3/s), while the energy consumption of a flat plate filter (EEAF) was about 170 W/(m^3/s) when there was no voltage applied. Thus, the study found that the EEPF could reduce energy consumption by 75%.

4.1.2.2. UVGI systems. According to HVAC guidelines issued by various institutions; it can be found that the application of UVGI systems is recommended to reduce the risk of airborne transmission by HVAC systems. Light with a wavelength between 100 and 400 nm is called ultraviolet (UV). Prescott and others [122] found that UV can be divided into UV-A (320 ~ 400 nm), UV-B (275 ~ 320 nm), UV-C (200 ~ 275 nm) and vacuum UV (100 ~ 200 nm). A virus is sensitive to the wavelength of UV-C, as UV-C can destroy the binding of DNA components and RNA, and deactivate the virus with sufficient irradiation intensity and time. There are two ways to introduce UV-C in HVAC systems. The first way is to use UV-C to irradiate the inner surfaces of cooling coils, drainage plates and AHUs so as to reduce the growth of viruses in these humid environments. A UV-C system consumes about 1% of the total energy consumption of an air-conditioning system per year as reported by Fencl [123]. The second way is to utilize UV-C to deactivate microorganisms in the airflow so as to achieve pandemic prevention and control. Study result in Ref. 35 found that installing UV-C in the ventilation ducts of HVAC systems killed more than 90% of indoor SARS-CoV-2 with a high energy efficiency, and the application of a sterilized UV-C source only increased energy consumption by 0.45%.

As described in Section 4.1.1, increasing ventilation rate is an important way to reduce the indoor transmission of SARS-CoV-2, but it can also increase HVAC system energy consumption by 2% to 264.5% as presented in Ref. 32. To alleviate this problem, researchers have carried out relevant studies. Noakes and others [124] established a regional infection risk model and found that the sterilizing effect of introducing UV devices with an average plane irradiance of 0.2 W/m^2 is the same as increasing the hourly air exchange rate from three to six. A study by Kanaan [125] also showed that utilizing upper indoor UVGI systems was a more economical way to reduce indoor bacterial concentration than increasing outdoor air volume. The rated power of UVGI systems is negligible compared to the power consumption of HVAC systems. It is true that the application of UV-C sterilization source increases the energy consumption of HVAC systems, but the total energy consumption only increases by 0.45% which is negligible as presented in Ref. 35.

4.1.2.3. Heat recovery devices. Operation guidelines for HVAC systems propose that it is necessary to increase outdoor air volume. However, increased outdoor air proportion significantly raises the energy consumption of HVAC systems. The high energy consumption of HVAC systems violates the goals of low carbon economy and environment protection. An indirect heat recovery exchanger can greatly reduce energy consumption caused by increased outdoor air volume, and meet the requirements of pandemic prevention and control. This solution is recommended in many HVAC guidelines. The study conducted in Ref. 31 indicates that a heat recovery device can reduce the average energy consumption of a HVAC system by 5.6%. Study in Ref. 30 analysed energy consumption at different minimum outdoor air ventilation rates, and pointed out that the energy consumption only increased by 7.6% and 21.6% with the help of an economizer when the ventilation rate was increased by 50% and 100%, respectively. Their results indicate that using heat recovery devices can maintain energy consumption at normal levels despite the introduction of a high ventilation rate. A study in Ref. 28 found that the application of heat recovery devices would maintain final energy consumption at a level similar to normal operation, despite ventilation rates increased by 50% for residential and office buildings and ventilation rates increased by 40% for schools. Research conducted by Ascione and others [126] demonstrated that space heating demand increased by only 51.6% with the application of heat recovery devices when the outdoor ventilation amount was increased from 7 L/s to 21 L/s. Therefore, it can be concluded that the application of heat recovery technology comes with significant energy conservation potential. In addition, heat recovery can mitigate the stress of increased HVAC system energy consumption arising from implementing pandemic prevention and control measures.

4.1.3. HVAC system operation schedules

To meet the needs of pandemic prevention and control, a HVAC system operation schedule undergoes changes to varying degrees according to the guidelines provided in the Section 3.2.3. Extra operation hours before and after a building is occupied are crucial to improving indoor air quality and reducing infection risks. Compared with the normal times, HVAC systems during the pandemic period require extended operation schedules, and this may have a significant impact on its energy consumption. A study by MacNaughton and others [127] indicates that an inappropriate operation schedule can result in a 20% energy cost increase. Escrivá-Escrivá and others [128] compared four kinds of scheduling techniques for HVAC systems in Spanish universities and the results showed significant impacts on energy consumption. Haniff and others [129] investigated HVAC system energy consumption with several different operation schedules and found that energy consumption increased by 4.48% when delaying one hour, and increased by 11.19% when delaying two hours. They also reported that energy consumption increased by 11.22% and 31.59% when preheating was started 1 hour and 3 hours in advance, respectively. Mokhtari and others [130] proposed that extending the HVAC operation schedules could significantly reduce the infection probability during the pandemic, albeit also resulting in an obvious increase in energy consumption. Their research indicates that energy consumption increased by 39.2% in summer and 35.7% in winter when the HVAC operation schedule was extended from 8 hours to 15 hours. Therefore, it can be confirmed that changing HVAC system operation schedules during the COVID-19 pandemic can result in increased energy consumption in various regions. We urgently need to find a trade-off between healthy indoor environments and high energy consumption, and innovations in HVAC systems are imperative.

4.2. Impacts of COVID-19 on HVAC system energy consumption

The energy consumption of a HVAC system depends on its efficiency, meteorological conditions and occupant behaviours. Based on the differences observed between HVAC system operation during the normal times and pandemic period, it is well-established that changing HVAC operation results in considerable increase in energy consumption. China is one of the world's major energy consumers, and it spreads across five different climatic zones with diverse meteorological conditions. Therefore, public buildings with central air-conditioning systems in China are taken as a typical case, and the impacts of the COVID-19 pandemic on energy consumption by HVAC systems are analysed from a temporal as well as a spatial perspective. The results of energy consumption variation in China are instructive, and the worldwide pattern of HVAC system energy consumption during the pandemic can be further investigated.

4.2.1. Temporal and spatial variations of HVAC systems

The analysis in this section is based on energy consumption statistics in Tsinghua University Building Energy Research Centre [131] of public buildings in China during the normal times. The increasing ratio of HVAC load between the normal times and pandemic period is calculated to estimate energy consumption in the pandemic period. The minimal amount of outdoor air during the normal times is obtained by the relevant guideline as presented in Ref. 103, and 100% outdoor air operation mode is assumed during the pandemic period as presented in Ref. 88. Only central air-conditioning systems in public buildings are considered. Furthermore, it is worth noting that public buildings mainly include office buildings, commercial buildings, medical buildings and so on.

Table. 8
Comparison of HVAC system energy consumption over time.

Period	Energy consumption (GWh)	Energy consumption intensity (kWh/m^2)	Primary energy (Mtce)	Primary energy intensity (kgce/m^2)	Increasing ratio %
Normal	485940	38	199	16	128
Pandemic	1108631	87	453	35	

The calculation process is as follows:

(1) HVAC load during the normal times

The total HVAC load during the normal times, $Q_{\text{total,n}}$, is calculated as:

$$Q_{\text{total,n}} = \sum Q_{\text{n}} \tag{1}$$

where Q is the hourly HVAC load provided by the equipment and subscript n is the normal times.

The HVAC load during the normal times, Q_{n}, is written as:

$$Q_{\text{n}} = Q_{\text{o,n}} + Q_{\text{r,n}} \tag{2}$$

where $Q_{\text{o,n}}$ is the HVAC load of outdoor air and $Q_{\text{r,n}}$ is the HVAC load of return air.

The HVAC load of outdoor air, $Q_{\text{o,n}}$, is written as:

$$Q_{\text{o,n}} = m_{\text{o,n}} \times |h_{\text{o}} - h_{\text{s}}| \tag{3}$$

where $m_{\text{o,n}}$ is the mass flow of outdoor air during the normal times, h_{o} is the enthalpy of outdoor air and h_{s} is the enthalpy of supply air.

The HVAC load of return air, $Q_{\text{r,n}}$, is written as:

$$Q_{\text{r,n}} = m_{\text{r,n}} \times |h_{\text{i}} - h_{\text{s}}| \tag{4}$$

where $m_{\text{r,n}}$ is the mass flow of return air and h_{i} is the enthalpy of indoor air.

(2) HVAC load during the pandemic period

The total HVAC load during the pandemic period, $Q_{\text{total,p}}$, is calculated as:

$$Q_{\text{total,p}} = \sum Q_{\text{p}} \tag{5}$$

where the subscript p is the pandemic period.

During the pandemic period, 100% outdoor air operation mode is assumed according to Ref. 88 and the HVAC load during the pandemic period, Q_{p}, is calculated as:

$$Q_{\text{p}} = Q_{\text{o,p}} \tag{6}$$

where $Q_{\text{o,p}}$ is the HVAC load of outdoor air.

The HVAC load of outdoor air, $Q_{\text{o,p}}$, is written as:

$$Q_{\text{o,p}} = m_{\text{o,p}} \times |h_{\text{o}} - h_{\text{s}}| \tag{7}$$

where $m_{\text{o,p}}$ is the mass flow of outdoor air during the pandemic period.

(3) Energy consumption of HVAC systems during the pandemic period

The increasing ratio of HVAC load between the normal times and pandemic period, α, is expressed as:

$$\alpha = \frac{Q_{\text{total,p}} - Q_{\text{total,n}}}{Q_{\text{total,n}}} \times 100\% \tag{8}$$

The energy consumption of HVAC systems during the pandemic period can be estimated based on the statistics of energy consumption during the normal times as presented in Ref. 131 using the following expression:

$$E_{\text{p}} = E_{\text{n}} \times (1 + \alpha) \tag{9}$$

where E_{p} is the energy consumption of HVAC systems during the pandemic period and E_{n} is the energy consumption of HVAC systems during the normal times.

The energy consumption of HVAC systems is analysed from a temporal perspective and the calculation results are presented in Table 8.

Table 8 indicates that the energy consumption of HVAC systems during the pandemic period increases by 128% compared with that during the normal times, which sounds the alarm on energy conservation. The change in operation strategy of HVAC systems plays a predominant role in this energy demand upsurge. The substantial increase of energy consumption is a consequence of increasing the share of outdoor air. A worldwide consensus has been reached that maximizing outdoor air as much as possible, and disabling air recirculation, is beneficial to mitigating the risk of airborne transmission. A guideline presented in Ref. 88 regarding HVAC operation issued in China recommends using an outdoor air ratio of 100% and disabling air recirculation. Consequently, increasing outdoor air volume and the switching off of air recirculation make HVAC systems work at the maximal load ratio, which results in higher energy demand than usual.

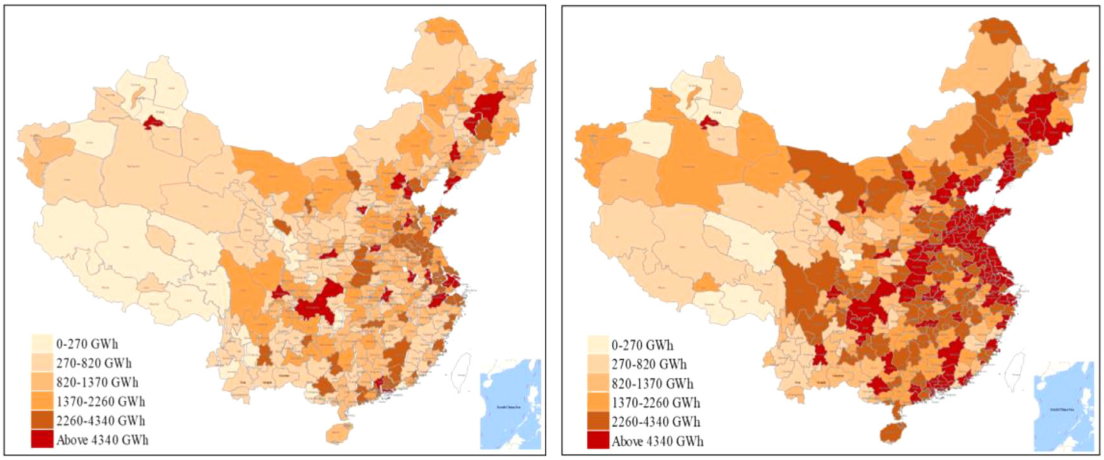
Energy consumption of HVAC systems is also compared spatially across China. Energy consumption of HVAC systems during the normal times and pandemic period is illustrated in Fig. 16. The energy consumption data is estimated based on energy statistics from Ref. 131 and statistics of public building area while the confidence interval of these statistics data is not provided. It is worth noting that the hourly variations of meteorological conditions and HVAC system operation efficiency can bring uncertainty to the energy consumption data. Furthermore, policies of work resumption in different cities and occupants' behaviour also impact the energy consumption of HVAC systems. The above uncertain factors are not considered in this paper and future work is needed to introduce these uncertainties to obtain more precise results of energy consumption.

The spatial distribution of energy consumption of HVAC systems has a clear pattern. From Fig. 16 (b) it is evident that the level of energy consumption in eastern China is higher than in western China, especially in the eastern coastal cities. This can be attributed to the higher urbanization of eastern China, and greater concentration of public buildings. Furthermore, it can be observed that the energy consumption of HVAC systems increases by a substantial magnitude during the COVID-19 pandemic. During the normal times, the cities with high HVAC system energy consumption (over 4340 GWh) account for 6.4% of China's total; these cities are mainly developed cities like Beijing, Shanghai, Tianjin and Guangzhou. However, the proportion rises to 30.3% during the pandemic period, and a number of cities surpass 4340 GWh of energy consumption. The highest HVAC system energy consumption in public buildings reaches to 55223 GWh in Shanghai during the pandemic.

The increasing ratio of HVAC system energy consumption in China is shown in Fig. 17. This indicates that in eastern as well as southern cities in China, the increase in energy consumption is much higher. It can be inferred that the energy consumption of each city varies with meteorological conditions and the concentration of public buildings, but further studies are needed.

In order to study the relationship between various influencing factors and the increasing ratio of energy consumption, the Pearson correlation coefficient is calculated. It is worth noting that the typical meteorological parameters as presented in Ref. 103, area of public buildings and increasing ratio of energy consumption in Chinese cities are used for the calculation. The Pearson correlation coefficient can be calculated with covariance as well as standard deviation. The formula used is given as:

$$r = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y} \tag{10}$$



(a) (b)

Fig. 16. Energy consumption of HVAC systems during the (a) normal times, and (b) pandemic period.

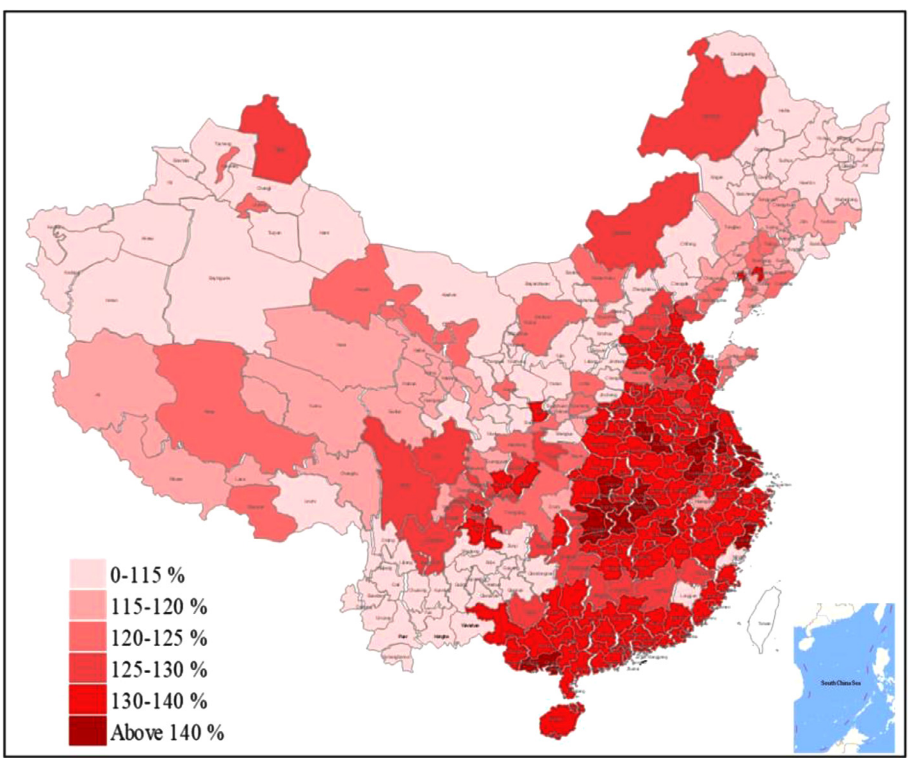


Fig. 17. Variation of HVAC system energy consumption during the normal times and pandemic period.

Table. 9
Results of Pearson correlation coefficients.

Season	Influencing factor	Pearson correlation coefficient
Winter	Dry-bulb temperature of outdoor air	-0.76
	Relative humidity of outdoor air	-0.43
Summer	Dry-bulb temperature of outdoor air	0.78
	Relative humidity of outdoor air	0.59
Both	Area of public buildings	0.13

where r is the Pearson correlation coefficient, x is the influencing factor, and y is the increasing ratio of HVAC system energy consumption in winter and summer.

The calculation results are shown in Table 9. The energy consumption of HVAC systems varies with heating load in the winter, and the dry-bulb temperature as well as relative humidity of outdoor air present a negative correlation with energy consumption. The results in summer are the opposite, with the energy consumption of HVAC systems increasing with the rise of outdoor air dry-bulb temperature and relative humidity. The outdoor dry-bulb temperature has the strongest impact on HVAC system energy consumption: the absolute value of the coefficient exceeds 0.75, which shows a high level of correlation. The effect of relative humidity is moderate: the absolute value of the coefficient is between 0.4 and 0.6. Public building area has the weakest impact compared with the above factors. Therefore, it is important to consider the variations of outdoor air in the analysis of HVAC system energy consumption.

Table. 10
Variations of HVAC system energy consumption in the five typical climatic zones.

Zone	Energy consumption during the normal times and pandemic period (GWh) 2019	2020	Increasing ratio (%) Winter	Summer	Total
Severe cold	56779.40	120042.31	123.74	82.90	111.42
Cold	172793.39	388154.60	117.42	135.88	124.64
Hot summer and cold winter	201124.19	473957.84	108.86	164.97	135.65
Hot summer and warm winter	47578.62	112323.48	93.40	168.36	136.08
Mild	7664.40	14152.64	107.51	18.28	84.65

4.2.2. Variations of HVAC system energy consumption in typical climatic zones

China is divided into five typical climatic zones to distinguish zones with different climate characteristics. These zones are the severe cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and mild zone. Owing to the variations of outdoor air parameters in these five zones, extra load demand and energy consumption of HVAC systems differ by climate zone. Therefore, it is meaningful to discuss the variations combined with climate features in these five climatic zones. Variations of energy consumption in the five climatic zones are presented and compared in Table 10. It can be seen that the increasing ratios of energy consumption in these five climatic zones are diverse.

Based on the analysis of Pearson correlation coefficients, the dry-bulb temperature of outdoor air plays an important role in increased energy consumption, and results in different increasing ratios in the five climatic zones. The total increasing ratios in the hot summer and cold winter zone and the hot summer and warm winter zone are quite close. The climate in the hot summer and cold winter zone is muggy in the summer and clammy in the winter. The cooling and heating load in this zone should be met by HVAC systems, and the increasing ratio is significant due to increased outdoor air volume during the pandemic. As for the hot summer and warm winter zone, it is scorching hot in the summer and warm in the winter. HVAC systems are mainly used to meet the cooling load. The increasing ratio in the summer is considerable, and even exceeds that of the hot summer and cold winter zone. In the cold zone, the climate is cold-dry in the winter and hot-humid in the summer. The increasing ratio of energy consumption is lower than in the hot summer and cold winter zone, due to the smaller cooling load. The total increasing ratio in the severe cold zone is lower than in other zones except the mild zone, which can be attributed to underdevelopment and less cooling load. The minimum impact occurs in the mild zone, because it boasts the least cooling load and the maximal outdoor air ratio is more acceptable in this zone.

Through the comprehensive analysis of energy consumption variations from diverse perspectives, it is clear that the COVID-19 brings both challenges and opportunities as reported by Jiang and others [132]. On the one hand, the substantial increase of HVAC system energy consumption brings challenges for the goal of peaking CO_2 emissions in 2030, as well as achieving carbon neutrality in 2060, and the high-level energy consumption of HVAC systems creates challenges for the power grid according to Werth and others [133]. On the other hand, increased energy consumption sets the stage for novel HVAC technologies, HVAC operation optimization methods, and the utilization of renewable energy.

5. Future challenges and innovations of HVAC systems

5.1. Challenges in the designing of HVAC systems

With the COVID-19 pandemic, existing HVAC systems are facing considerable challenges. The above discussions demonstrate that there is a close relationship between HVAC systems and airborne transmission of SARS-CoV-2. Therefore, the pandemic prevention guidelines put forward by various institutions attach great importance to the role of HVAC systems during the pandemic as highlighted in Ref. 26 and 97, and by CAR [134]. Inappropriate airflow patterns in HVAC systems may aggravate the spread of SARS-CoV-2 in enclosed environments and increase the probability of infection as presented in Ref. 93. Conversely, appropriate HVAC system operation can inhibit the spread of SARS-CoV-2 indoors but the increased energy consumption is obvious. It is imperative to solve two main challenges concerning HVAC systems, while also guaranteeing that they can operate stably: 1) how can HVAC designs adapt to both the normal situation and pandemic situation simultaneously; 2) and how can HVAC systems operate in a low energy consumption mode during the pandemic.

Considering the first question, how can HVAC designs adapt to both the normal situation and pandemic situation simultaneously? Three key issues have come to light: a) conventional HVAC systems have little ability to filter and kill viruses as revealed by Siddique and others [135], and to reduce the risk of SARS-CoV-2 spreading and cross infection during the pandemic; b) current HVAC systems are designed according to previous guidelines, and thus may not meet requirements during the pandemic, and fail to provide enough ventilation rate to dilute indoor air pollutant concentration; and c) HVAC system capacity may be insufficient to undertake the full heating and cooling load as presented in Ref. 50 with disabling air recirculation recommended to prevent the risk of cross infection. Based on current studies, HEPA filters are efficient to mitigate the transmission of SARS-CoV-2, as reported by Bhatia [136] and Azimi and others [137]. Furthermore, UVGI systems as presented in Ref. 35 and 125 can be installed in HVAC systems to sterilize indoor air according to Ref. 55. Dai and Zhao [138] recommended simultaneously reducing the ventilation rate to the largest extent possible while ensuring stable operation of HVAC systems during the pandemic. Other more efficient ventilation methods such as personalized ventilation are also recommended to improve the utilization of clean air, thus reducing the required overall ventilation rate during the pandemic as reported by Melikov [139 and 140]. The aforementioned measures can help to ease the conflict caused by HVAC systems switching between normal and pandemic modes.

When a pandemic occurs, disabling air recirculation system is recommended to prevent the virus from spreading indoors. Meanwhile, increasing the outdoor air rate is necessary, and indoor temperature as well as relative humidity should be controlled to inhibit the spread of viruses. Giampieri and others [141] assessed solutions for airborne viral transmission reduction in HVAC systems, Santos and others [142] studied best practices on HVAC designs to minimize risk of COVID-19 infection indoors. The effects of air temperature and relative humidity on the survival of the SARS-CoV-2 was investigated by Casanova and others [143]. In addition to the challenges discussed above, pandemics bring high energy consumption that cannot be ignored. Then, the following question emerges: how can we make HVAC systems operate in a low energy consumption mode during the pandemic period? Exploring the use of phase change materials in conjunction with HVAC systems may be one option. Wang and others [144] proved that applying of phase change materials in refrigeration systems could save the energy consumption by 8% and increase cooling coefficient of performance (COP) by 6%. Zhao and Tan [145] proved that integrating a phase change material thermal storage system with a conventional air-conditioner could increase COP by 25.6% and energy consumption could be mitigated. Franco and Schito [146] reported that appropriate and effective control strategies for the ventilation rate can also achieve energy conservation. Heat recovery devices, especially heat pipe heat exchangers (HPHE), may be the most immediate means for dealing with the high energy consumption caused by high ventilation rate. Pekdogan and others [147] carried out an experimental study on a decentralized ventilation system with HPHE. Shen and others [148] investigated liquid desiccant regeneration with heat recovery heat pipe systems. Madiana-Idayu and Riffat [149] reviewed heat recovery technologies for building applications. Sukarno and others [150] utilized HPHE to reduce HVAC system energy consumption in an isolation hospital room. Furthermore, liquid drying technology with low-grade consumption is again attracting researchers' attention, for controlling indoor temperature and relative humidity, as well as for deactivating viruses to reduce the concentration of indoor pollutants as presented in Ref. 142.

It can be concluded that some current measures adapted by HVAC systems can play a role in responding to pandemics. But this is far from enough to provide an efficient response to a sudden pandemic. More investigation and efforts are still needed to further improve HVAC systems.

5.2. Future impacts of COVID-19 on HVAC systems

Through the above review and discussions, it can be seen that some pandemic prevention and control measures will result in increased HVAC system energy consumption during the pandemic period. In addition, the current design of HVAC systems (according to the guidelines based on normal operation) cannot provide adequate prevention during a pandemic. Auxiliary equipment recommended by the guidelines at this stage, such as HEPA filters, UVGI systems, and heat recovery devices, are still not mandatory parts of HVAC systems. After the sudden spread of COVID-19, health replaces comfort as the primary consideration of air-conditioning systems. Therefore, the aforementioned equipment should be important and necessary components of HVAC designs in the future. However, most of the current research activities on the above equipment are based on them working under normal conditions, and studies on pandemic conditions are few. Hence, more efficient HEPA filters, UVGI systems, and heat recovery devices adapted to multiple situations should be urgently studied and developed. Moreover, novel mechanical ventilation methods and control strategies that can significantly improve effective ventilation volume to provide healthy indoor environments both in normal and pandemic conditions should be another research focus of the future HVAC system. Meanwhile, the recently proposed mobile medical care system proposed by Fraunhofer [151] that can provide medical care to the public as a crucial addition to the existing healthcare infrastructure in crises and emergencies also puts forward a new direction for innovations in HVAC systems.

6. Conclusion

To reveal the impacts of COVID-19 on the operation and energy consumption of HVAC systems, this paper addressed the following elements: (a) airborne transmission characteristics of SARS-CoV-2 in enclosed spaces; (b) operational variations of HVAC systems proposed by various guidelines during the pandemic; (c) the quantitative impact of the guideline-recommended countermeasures on the energy consumption of HVAC systems; and (d) future impacts on HVAC system innovations and research trends.

Based on available literature, it can be concluded that airborne transmission is the major propagation mode of SARS-CoV-2 in enclosed spaces. Concrete measures including mixed ventilation, displacement ventilation, as well as personalized ventilation can play a major part in mitigating infection risks when applied to specific scenarios. Various institutions and agencies have issued guidelines to regulate the operation mode of HVAC systems during the pandemic. The common countermeasures include: increasing outdoor air ratio combined with rational airflow pattern, extending operation schedules, maintaining negative pressure in special areas, and applying auxiliary equipment. However, discrepancies of guidelines exist in choosing set-points of temperature and relative humidity, and in the application of rotary heat exchangers. The transformation of HVAC operation improved air quality but also increased energy demand. Based on a case study of China, it is found that during the pandemic the energy consumption of HVAC systems increases by 128%. New challenges emerge for the design and operation of HVAC systems in the future. Attention should be paid to adapting HVAC designs to the normal situation as well as pandemic situation simultaneously, and to operating HVAC systems in a relatively low energy consumption mode during the pandemic period. Appropriate application of auxiliary equipment and improvement of operation strategy are beneficial to assuring indoor air quality and energy conservation. In the future, studies should focus on the efficient operation of HVAC, and heath will be the primary consideration of HVAC system designs and operations. With the development of intelligent technology, it is possible to monitor and predict indoor air quality and infection risks. Furthermore, artificial intelligence is promising to realize the optimal operation of HVAC systems, and the trade-off between indoor air quality and energy consumption can be solved by multi-objective algorithms such as genetic algorithm and particle swarm algorithm.

Conflict of interest

The authors declared that they have **no** conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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